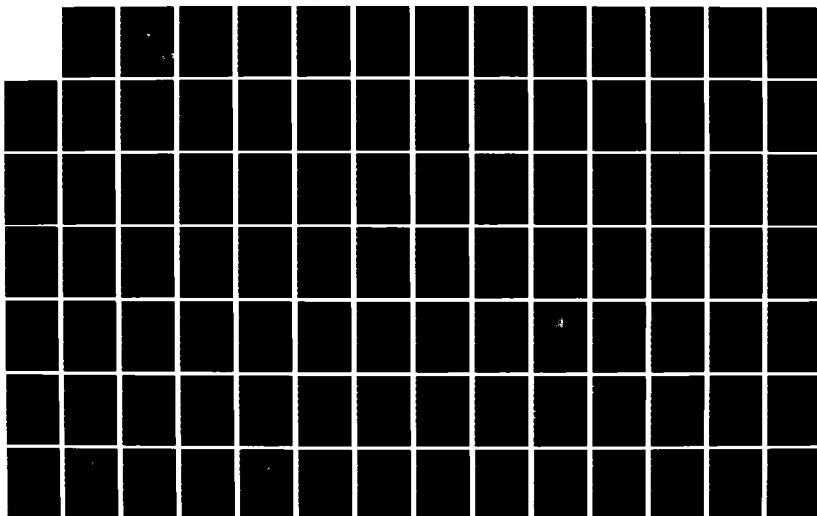CONTROL SYSTEMS FOR A DUAL MOTOR HIGH SPEED MOTION
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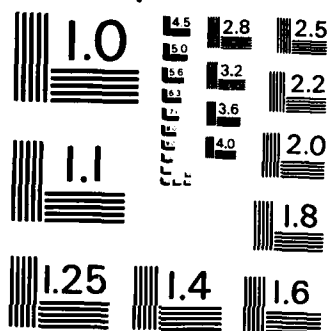MICROCOPY RESOLUTION TEST CHART

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

CONTROL SYSTEMS FOR A DUAL MOTOR HIGH
SPEED MOTION PICTURE CAMERA

by

Edward Y. Brewster

September 1985

Thesis Advisor: G. J. Thaler

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This thesis studies the control of a dual motor high speed motion picture camera. This camera is a modification of the one motor cameras presently in use today. First the system model is developed and then the control system is examined for the ideal tachometer. Next, non-ideal characteristics of the tachometer signal as derived from an optical tachometer are discussed. Included in this section is the need to have pretensioning prior to the filming and deceleration at the end of the filming. The remainder of the thesis examines phase locked loop techniques for speed control of the high speed camera.

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Control Systems for a Dual Motor
High Speed Motion Picture Camera

by

Edward Y. Brewster
Lieutenant, United States Navy
B.S.E.E., University of Kansas, 1979

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING
and
ELECTRICAL ENGINEER

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2

ABSTRACT

This thesis studies the control of a dual motor high speed motion picture camera. This camera is a modification of the one motor cameras presently in use today. First the system model is developed and then the control system is examined for the ideal tachometer. Next, non-ideal characteristics of the tachometer signal as derived from an optical tachometer are discussed. Included in this section is the need to have pretensioning prior to the filming and deceleration at the end of the filming. The remainder of the thesis examines phase locked loop techniques for speed control of the high speed camera.

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I. INTRODUCTION

A high speed motion picture camera has been a useful tool to the scientist, engineer, and analyst for a long time. Through high speed photography they can get a good look at events and interactions that are normally too fast for the human eye to see. At present cameras which attain speeds of 10,000 frames per second are available, but the desire is to reach even higher film speeds.

In the present cameras there is usually only one motor and this is attached to the take up reel (Figure 1.1). When the camera is started up the take up reel pulls the film off the supply reel and through the camera. The tension
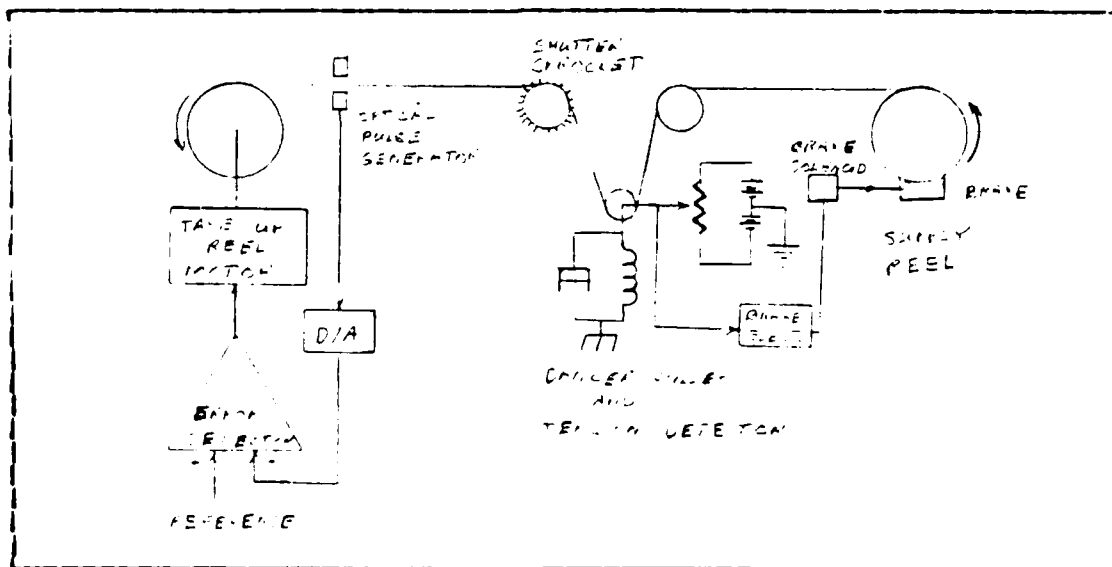
Figure 1.1   Diagram of Camera Using Only One Motor

in the film is maintained by a dancer pulley assembly and a brake mounted on the supply reel. This type of camera has

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reached 10,000 frames/sec, but as higher speeds are attempted the time to reach steady state becomes prohibitive and there is little film remaining to take pictures at this speed.

The camera of the present is not adequate, so a new approach is needed and one of the simplest is to put an additional motor on the supply reel. By doing this the torque load on the take up reel is reduced and the system should be able to reach steady state speed faster. This means that more film is available to take pictures at the desired speed.

The basic operation will be similar to a one motor camera, and Figure 1.2 shows a basic working diagram of the camera. When the camera is turned on the film is placed under tension. When the film event starts the take up reel
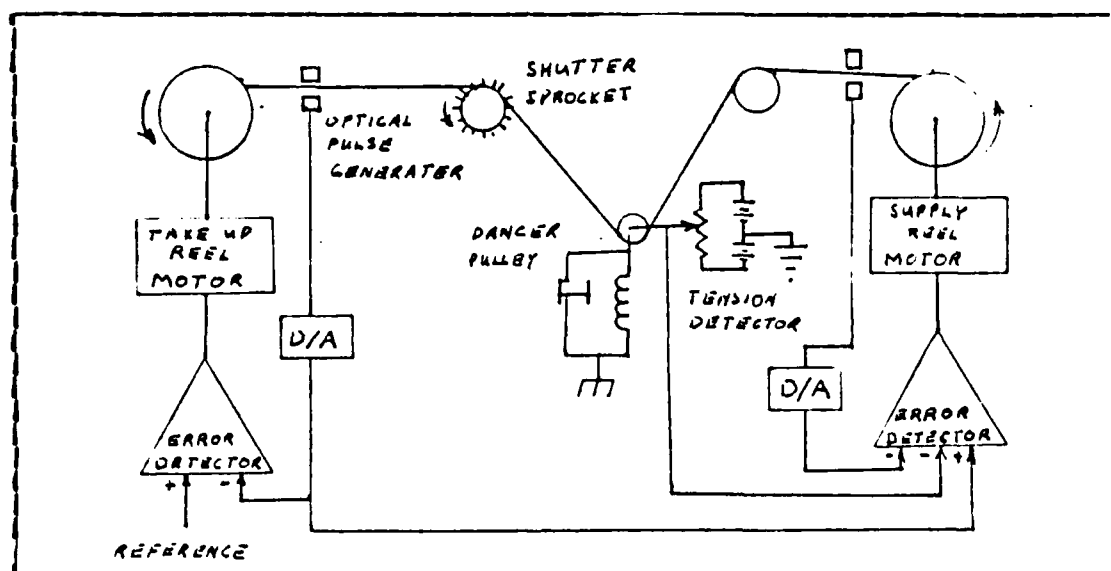
Figure 1.2   Diagram of Camera Using Two Motors

responds to a step or a ramp input and accelerates up to the ordered speed. At the same time the supply reel is also

accelerating in response to its input command. When the desired film speed is attained the two motors work to keep it constant through velocity feedback. The desire is to reach a steady state speed of 15,000 frames/sec in 50 feet of film or less, and to maintain the ordered steady state speed as closely as possible. At the steady state speed the tension must also be regulated so that the film isn't stretched or allowed to pile up and foul up the internal mechanism. To do this a voltage error signal that is proportional to the tension is used to speed up or slow down the supply reel motor. At the end of the film the system must be decelerated so that film isn't allowed to fly around at high speeds. If the speed is excessive the end of the film, up to 50 feet, can be broken and torn. The goal here is to decelerate to a safe speed in the last 50 feet of film. Also the camera should be able to start up, take pictures, and stop when lower frame speeds are desired.

The concept is simple but the control system can be elaborate. The motors must work synchronously or the film tension will vary excessively causing the film to stretch or pile up. The control of film tension through either the supply or the take up reel speed causes coupling between the speed loop and the tension loop. The amount of coupling and its affect will vary depending on the type of speed control used. The speed control can be through tachometer feedback, optical tachometer feedback, or a phase locked loop.

This thesis will examine the two motor camera in much the same way that Sameniego [Ref. 1] examined the one motor camera, through computer simulation. Solutions to the control problems are obtained that closely approach the design goals. The equations and theory that will form the basis for the simulations are developed in the next chapter. In Chapter 3 the control system based on an ideal tachometer is developed. First a one reel system is modeled and tested.

Then another reel is added and finally in successive steps a dancer assembly, tension loop, and a shutter assembly are added until a complete two motor camera control system has been developed and tested. Chapter 4 examines the problems of using an optical tachometer and how pretensioning and deceleration of the film are accomplished. The last chapter, chapter 5, involves phase locked loop speed control of the camera to get better speed regulation.

The appendices contain a derivation of the windage torque constant and block diagrams and program listings for the different control systems. The derivation of the windage torque is contained in Appendix A. The block diagrams for the control schemes developed in Chapter 3 are in Appendix B as well as the program listing for the complete camera as developed by the end of Chapter 3. The program for the optical tachometer from Chapter 4 is contained in Appendix C and the phase locked loop program listings are in Appendix D. These programs are written in DSL (Dynamic Simulation Language) for execution on the IBM 370 computer.

II. MATHEMATICAL MODELING OF CAMERA COMPONENTS

A. INTRODUCTION

The high speed camera is driven by two permanent magnet DC motors. The motors are driven by a pulse width modulated power supply, the output of which is determined by the error signal. The pulse width modulator introduces a limiter non-linearity into the system. Another non-linearity is the load itself because the inertia of each reel is constantly changing.

These non-linearities make it difficult to obtain analytical relationships to describe the dynamic behavior of the camera. It is possible to obtain analytical results if the above non-linearities are ignored. Though the results are not valid for the total range of operation, they can give an indication of what to expect.

The first step is to determine the mathematical equations that describe each part of the system. These equations are then used to develop computer simulation programs and transfer functions that aid in the analysis of the system. As each part of the camera is modeled mathematically the corresponding code for the simulation will also be presented. Since there are non-linearities in the system which prevent complete analytical results the bulk of the analysis and testing was done through computer simulation studies.

B. D.C. MOTOR EQUATIONS

The permanent magnet DC motor is well understood and the equations which describe its behavior have been developed in many texts [Ref. 2: p. 181]. Figure 2.1 shows the model

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from which the following equations and the block diagram of Figure 2.2 are derived.

The electrical equations are:

$$e_a(t) = R_a i_a(t) + L_a d(i_a(t))/dt + e_b(t) \qquad (2.1)$$

$$e_b(t) = K_b W_m(t) \qquad (2.2)$$

Substituting 2.2 into 2.1 and grouping all terms with $i_a(t)$ on one side yields

$$R_a i_a(t) + L_a d(i_a(t))/dt = e_a(t) - K_b W_m(t) \qquad (2.3)$$
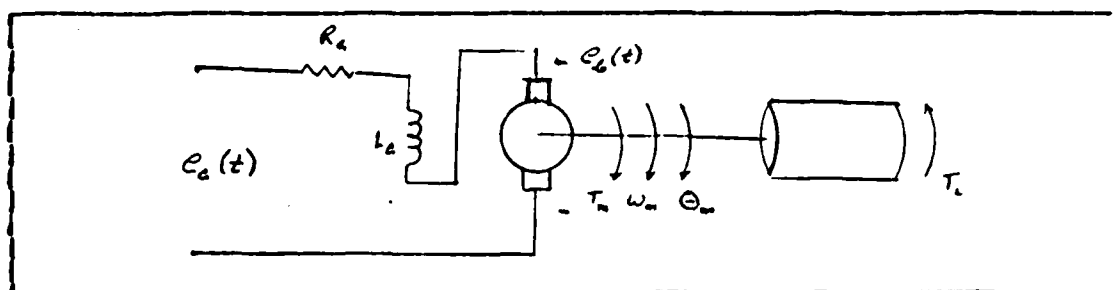
Figure 2.1   D.C. Motor, Schematic Diagram

Taking the Laplace Transform of 2.3:

$$I_a(s)(R_a + L_a s) = E_a(s) - K_b W_m(s) \qquad (2.4)$$

Rearranging

$$I_a(s) = \frac{1/R_a}{s L_a/R_a + 1} (E_a(s) - K_b W_m(s)) \qquad (2.5)$$

The equation of motion is written as follows:

$$J_{TOT}\ddot{\Theta}_m + B_m\dot{\Theta}_m = T_{TOT} \qquad (2.6)$$

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The input to equation 2.6 ,T_{TOT} , is the sum of all the torques acting on the motor shaft. This includes motor torque, load torque, and windage torque. The term J_{TOT} (total inertial load) is composed of the sum of the motor moment of inertia and the load moment of inertia which will be discussed later.

$$T_m = K_T I_a \tag{2.7}$$

$$T_{TOT} = T_m + T_L + T_\omega \tag{2.8}$$

$$J_{TOT} = J_m + J_L \tag{2.9}$$

Substituting $w_m = \dot{\theta}_m$ into 2.6 and taking the Laplace transform

$$W_m(s)(J_m s + B_m) = T_{TOT}(s) \tag{2.10}$$

Rearranging

$$W_m(s) = \frac{T_{TOT}}{J_{TOT}s + B_m} \tag{2.11}$$

Now utilizing equations 2.5 through 2.11, the block diagram in Figure 2.2 can be drawn. If the load torque and windage torque are neglected and the total inertia is assumed to be constant, then the following transfer function results.

$$\frac{W(s)}{E(s)} = \frac{K_T}{(J_{TOT}s + B_m)(L_a s + R_a) + K_T K_b} \tag{2.12}$$

Multiplying out the denominator and setting the coefficient of the highest power of s equal to one yields

$$\frac{W(s)}{E(s)} = \frac{K_T/J_{TOT}L_a}{s^2 + \dfrac{B_m L_a + J_{TOT}R_a}{J_{TOT}L_a}s + \dfrac{B_m R_a + K_T K_b}{J_{TOT}L_a}} \tag{2.13}$$

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The equations of the motor have all been derived and the simulation program is listed in Figure 2.3
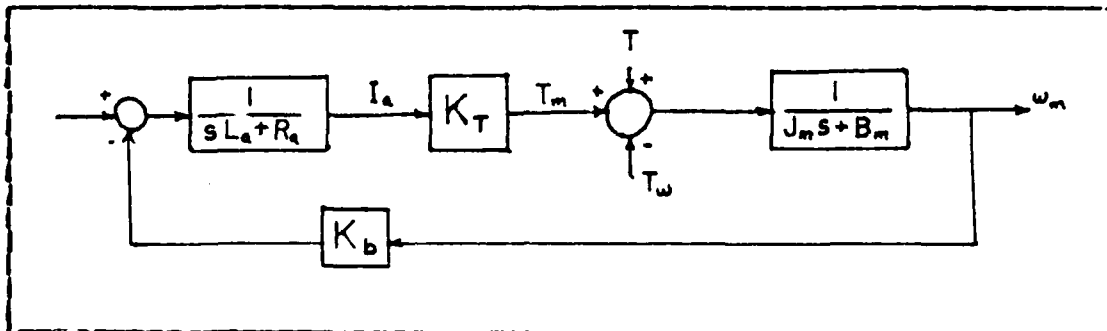
Figure 2.2   D.C. Motor, Block Diagram

```
VFILME = VFILM - VFILMS
DIFF = 100.*VFILME
EAS = LIMIT(0.0,200.0,DIFF)
BEMFS = KBEMF*PHIDOT
IASE = (EAS - BEMFS)*KE
IAS = REALPL(0.0,TAU,IASE)
TMS = KTS*IAS
PHIDDT = TMS/JS - BS*PHIDOT/JS
PHIDOT = INTGRL(0.0,PHIDDT)
```

Figure 2.3   DC Motor Simulation Program

C.   SUPPLY AND TAKE UP REEL EQUATIONS

The equations for the supply and the take up reels are the same except for the fact that in the supply reel the radius of the load is constantly decreasing while in the take up reel the radius of the load is constantly increasing. Therefore the equations for the supply reel will be developed and at the end the take up reel equations will be presented.

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The equations for load torque and load inertia depend on the amount of film on the reel. The radius will change from
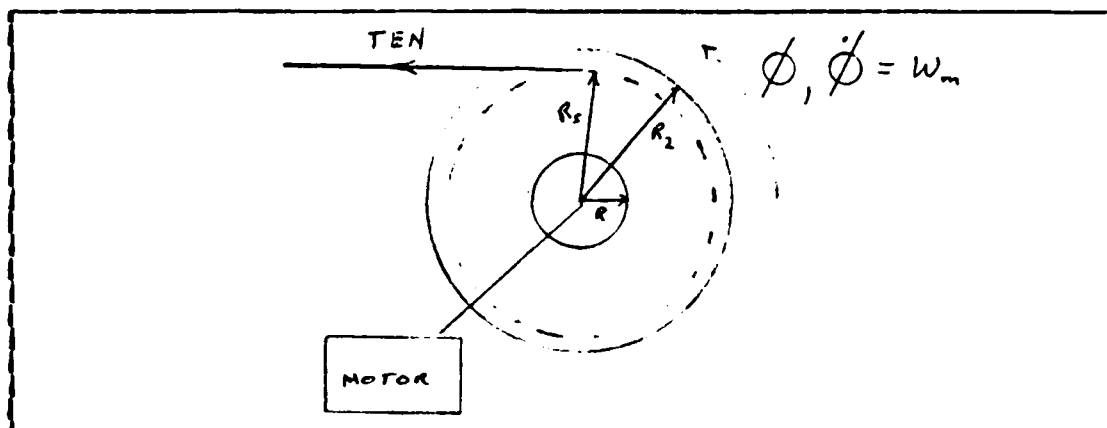
Figure 2.4   Supply Reel, Schematic Diagram

R2 to R as the film is removed. The radius of the supply reel, RS, is a function of the supply reel displacement (ϕ).

$$RS = R2 - (\phi \cdot H / 2 \cdot \pi) \qquad (2.14)$$

Using this variable the equations for the torque (TLS) exerted by the load and the load inertia (JSFILM) due to the film on the reel can be written.

$$TLS = RS \cdot TEN \qquad (2.15)$$

$$JSFILM = 0.5 \cdot MS \cdot (RS^2 + R^2) \qquad (2.16)$$

$$MS = \pi \cdot (RS^2 - R^2) \cdot W \cdot RHO \qquad (2.17)$$

There is another component of the load inertia and that is the inertia of the empty reel (JO) and the motor itself (JM). The final equation for the inertia of the supply reel is:

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$$JS = JM + JO + JSFILM \qquad (2.18)$$

The last piece to the supply reel equations is the torque due to windage. This is a drag on the system due to the outer edge of the reel moving through the air and it is proportional to the square of the motor speed in radians per second. The derivation of the windage torque constant (KW) is in Appendix A.

$$TWSUP = KW \cdot (PHIDOT)^2 \qquad (2.19)$$

The program code for the supply reel is listed in Figure 2.5

```
RS = R2-(PHI*H/2*PI)
MS = PI*(RS**2 - R**2)*W*RHO
JSFILM = 0.5*MS*(RS**2 + R**2)
JS = JM + JO + JSFILM
TWSUP = 0.00016*(PHIDOT**2)
PHIDDT = (TMS - TWSUP)/JS - BS*PHIDOT/JS
PHIDOT = INTGRL(0.0,PHIDDT)
PHI = INTGRL(0.0,PHIDOT)
VFILMS = RS*PHIDOT
```

Figure 2.5   Supply Reel Program

As stated previously the equations for the take up reel are similar. The differences lie in the calculation of RT, the take up reel radius, and whether the load torque adds or subtracts.

$$RT = B + (\psi \cdot H/2 \cdot \pi) \qquad (2.20)$$

The moment of inertia and load torque equations are now the same, but the variables have been renamed for clarity and programming.

$$MT = \pi \cdot (RT^2 - R^2) \cdot W \cdot RHO \tag{2.21}$$

$$JTFILM = 0.5 \cdot MT \cdot (RT^2 + R^2) \tag{2.22}$$

$$JT = JM + JO + JTFILM \tag{2.23}$$

$$TLT = TEN \cdot RT \tag{2.24}$$

$$TWTAK = KW \cdot (PSIDOT)^2 \tag{2.25}$$

In the take up reel both the load torque, TLT, and the windage torque , TWTAK, oppose the motor torque, TMT. In the supply reel the load torque TLS, aids the motor torque, TMS.

$$T_{Tot\,sup} = TMS + TLS - TWSUP \tag{2.26}$$

$$T_{Tot\,TAK} = TMT - TLT - TWTAK \tag{2.27}$$
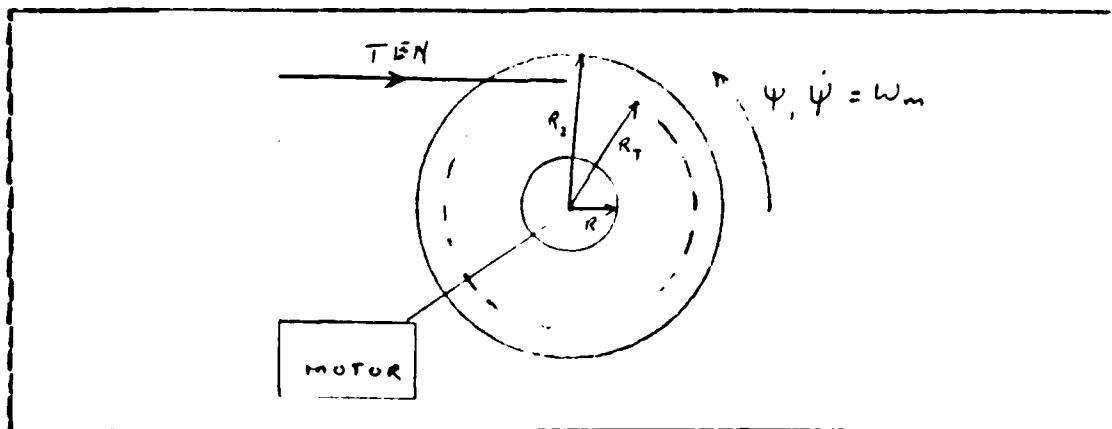
Figure 2.6   Take Up Reel, Schematic Diagram

Figure 2.6 shows the model of the take up reel. Figure 2.7 below shows the DSL program for the take up reel.

D. TENSION LOOP AND FILM TENSION EQUATIONS

In the camera there is a dancer pulley and spring

```
RT = R + (PSI*H/(2*PI))
MT = PI*(RT**2 - R**2)*W*RHO
JTFILM = 0.5*MT*(RT**2+R**2)
JT = JM + JO + JTFILM
TWTAK = 0.000016*(PSIDOT**2)
PSIDDT = (TMT - TWTAK)/JT - BS*PSIDOT/JT
PSIDCT = INTGRL(0.0,PSIDDT)
PSI = INTGRL(0.0,PSIDOT)
VFILMT = RT*PSIDOT
```

Figure 2.7   Take Up Reel Program

assembly which applies and maintains the tension in the film. As tension is applied the film will stretch which
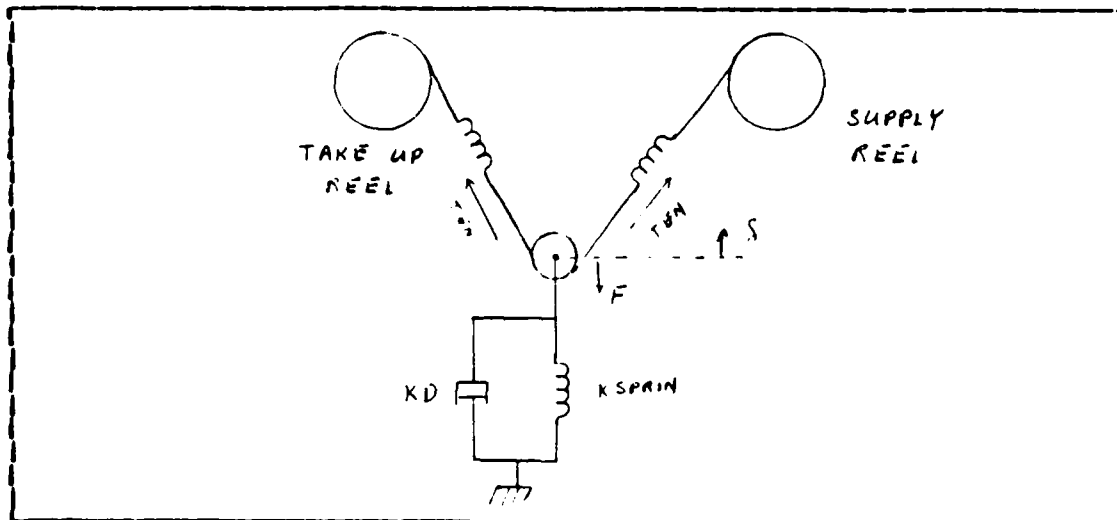
Figure 2.8   Dancer Pulley Tensioning Assembly

means that it must be modeled as a spring. This portion of the camera is shown in Figure 2.8

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The motion of the dancer pulley is described by taking the summation of the forces acting on it and setting them equal to zero. This equation is then solved for the acceleration. The displacement is the double integral of the acceleration. From mechanics the sum of the forces is:

$$M_{OAN} \cdot \ddot{\delta} + KD \cdot \dot{\delta} + KSPRIN \cdot \delta = 2 \cdot TEN \qquad (2.28)$$

$$\ddot{\delta} = (2 \cdot TEN - KD \cdot \dot{\delta} - KSPRIN \cdot DISTEN)/M_{OAN} \qquad (2.29)$$

In equation 2.29 all values except TEN (film tension) are defined. The film tension comes from the amount of stretch in the film and the film spring constant. The film spring constant was derived from the following table of data by using linear regression to get the slope.

TABLE I
FILM STRETCH CHARACTERISTICS FOR ONE FOOT OF FILM

TENSION (lbs)	STRETCH (in)
0.0	0.0
9.5	0.09
14.0	0.125
22.0	0.156
26.0	0.190
28.0	0.218

From the data in Table I the film spring constant (KFILM) was found to be 2180 oz/in. The film stretch is calculated by subtracting the amount of excess film in the loop and the change in the dancer pulley displacement from its initial starting point (DISP). Any difference indicates film stretch.

$$TEN = KFILM \cdot (DELTL - 2 \cdot DISP) \tag{2.30}$$

The calculation of the amount of change in film in the loop (DELTL) can be a problem. If the amount of film removed from the supply reel and the amount of film wound onto the take up reel are calculated and subtracted, the simulation has problems. This is because the computer is subtracting two large and nearly equal numbers. The rounding and truncation in the computer representation of these numbers causes significant errors in the answer. To avoid this problem the change in film in the loop was calculated as the integral of the difference in the speed of the film coming off the supply reel and the speed of the film winding onto the take up reel. The equations are shown below and the program code is listed as Figure 2.9 .

$$VFILMD = VFILMT - VFILMS \tag{2.31}$$

$$DELTL = \int VFILMD \, dt \tag{2.32}$$

```
VFILMD = VFILMT - VFILMS
DELTL = INTGRL (0.0,VFILMD)
```

Figure 2.9   Calculation of Length of Film in the Loop

Figure 2.10 below is the DSL program code to simulate the dancer and tension loop.

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E.   PULSE WIDTH MODULATION

The power supply for the motors is pulse-width modu-
lated. The basic circuit for the pulse-width modulator is

```
    DISPAC = (2.*TEN - KD*DISPVE - KSPRIN*DISTEN)/MDAN
    DISPVE = INTGRL(0.0,DISPAC)
    DISP = INTGRL(-0.0375,DISPVE)
    DISTEN = 2.0375 + DISP
    TEN = KFILM*(DELTL - 2*DISP)
```

Figure 2.10   Dancer and Tension Program

shown in Figure 2.11 .   The reference signal is a 10 KHz
triangular wave that oscillates between 0 and 10 volts. The
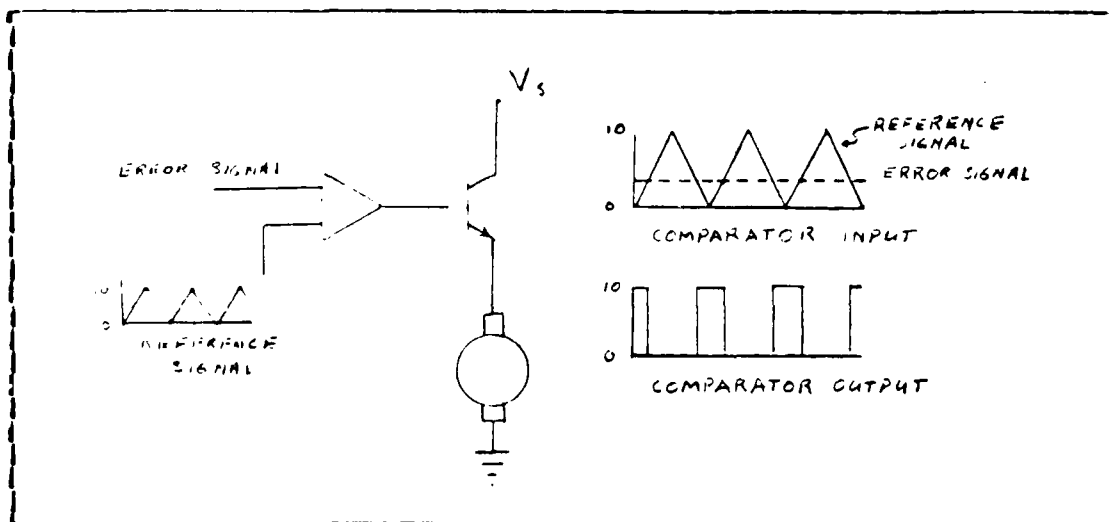
Figure 2.11   Pulse Width Modulated Power Amplifier.
Schematic Diagram

triangular wave and the input signal are fed into a compa-
rator.   The error signal is a DC signal that is the summa-
tion of all control signals and is limited to values between

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0 and 10 volts. The comparator compares the instantaneous values of these two signals which gives an output to the power switch as shown in Figure 2.11. When the error signal is greater than the reference signal then the comparator output is high which turns the power switch on. In this manner as the error signal approaches zero, the pulse width out of the comparator and therefore the pulse width of the power signal decreases. Figure 2.12 is the program code to simulate the pulse width modulated power supply.

```
      IF (N.EQ.1) VREF = 200000.*(TIME-A*.00005)+.00000001
      IF (N.EQ.2) VREF = 10.-200000.*(TIME-A*.00005)
      IF (VREF.GT.0.0.AND.VREF.LT.10.0) GO TO 10
      IF (VREF.LE.0.0) N = 1
      IF (VREF.GE.10.0) N = 2
   10 CONTINUE
      EAS = 0.0
      IF (VREF.LT.VCCMS) EAS = VS
```

Figure 2.12   DSL Program for Pulse-Width Modulation

The output of the pulse-width modulator can be described by a DC voltage level and an AC voltage ripple [Ref. 3: p. 114]. The AC ripple is at the same frequency as the triangular wave input to the comparator. Since this frequency is much greater than the motor bandwidth it is attenuated by the motor. Therefore the DC level determines the input to the motor. The DC level is a gain times the error or input signal.

$$E_{ouT} = \frac{V_{cc}}{V_\rho} - E_{iN}$$ (2.33)

Therefore in transfer function form it becomes a straight gain block. Calling this gain P the transfer function for

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the whole system can be written as:

$$\frac{W(S)}{E(S)} = \frac{P K_T / J_{ToT} L_a}{S^2 + \frac{B_m L_a + J_{ToT} R_a}{J_{ToT} L_a} S + \frac{B_m R_a + K_T K_b}{J_{ToT} L_a}} \qquad (2.34)$$

F. SHUTTER ASSEMBLY

The final piece of the camera that needs to be modeled
is the shutter assembly. The shutter is an inertial load on
the film, but it also breaks the film up into two sections
that must both be modeled as springs (Figure 2.13). The
modeling of the film as a spring has already been discussed
in section D above. The section of the film from the take
up reel to the shutter assembly is 4.75 inches long and has
a spring constant of 5507 oz/in. The tension in this section
of film is determined in the same manner as the tension of
the film in Figure 2.10. The other section of film is 7.25
inches long and its spring constant is 3609 oz/in. Here the
film tension is found by calculating the actual film stretch
or compression and multiplying this by the spring constant.
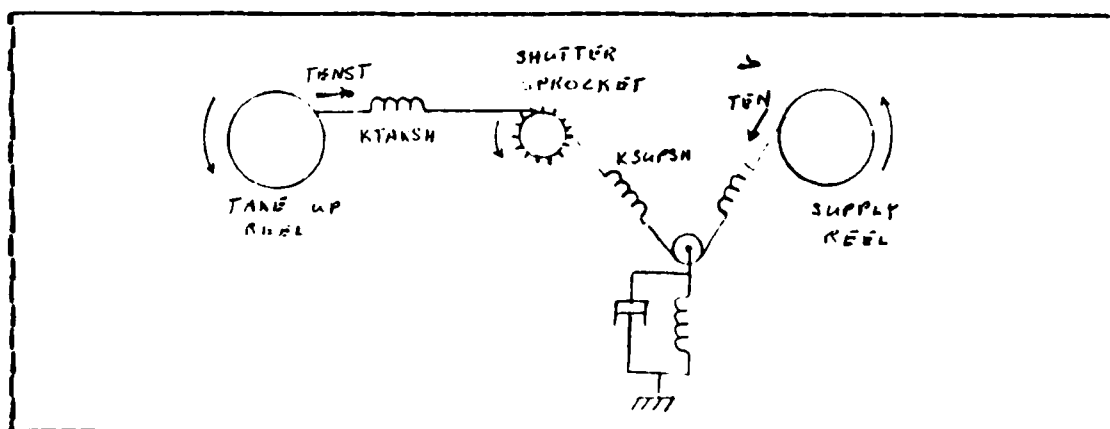
Figure 2.13   Shutter Assembly, Schematic Diagram

The shutter speed is determined by the forces acting on the
shutter sprocket. In this case the only forces acting on the

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shutter are the tensions from the two sections of film. The difference in tension acts on the sprocket to produce an angular acceleration as shown in equation 2.35 .

$$\ddot{\theta} = R_{SHUT} \cdot (TEN_{ST} - TEN_{SS}) / J_{SHUT} \qquad (2.35)$$

$$\dot{\theta} = \int \ddot{\theta} \, dt \qquad (2.36)$$

The DSL program that simulates this portion of the camera is shown in Figure 2.14 .

```
THEDDT = RADSH*(TENST - TEN)/JSHUT
THEDOT = INTGRL(0.0,THEDDT)
VSHUT = RADSH*THEDOT
VDIFFT = VFILMT - VSHUT
LOCPST = INTGRL(0.0,VDIFFT)
VDELTL = VSHUT - VFILMS
LOOPSS = INTGRL(0.0,VDELTL)
TENST = LOOPST*KTAKSH
DISPAC = (2.*TEN - KD*DISPVE - KSPRIN*DISTEN)/MDAN
DISPVE = INTGRL(0.0,DISPAC)
DISP = INTGRL(0.0,DISPVE)
DISTEN = .0103 + DISP
TEN = KSUPSH*(LOOPSS - 2*DISP)
```

Figure 2.14   Shutter Assembly Simulation Program

III. SPEED LOOP CONTROL (IDEAL)

A. INTRODUCTION

One very direct approach to speed control is to feed back the actual film speed. This signal is compared to the reference and the error signal is then used to drive the motor through the pulse width modulator. This approach is direct and appears to be simple, but the system is such that to keep the linear velocity of the film constant the motor must continually speed up at the supply reel and do just the opposite at the take up reel.

This chapter will look at the motor requirements and the development of the camera model. The model will be developed by first examining the supply reel, then the take up reel, and finally both reels will be connected and a tension loop inserted.

B. MOTOR SELECTION

The desire in this camera design is to achieve linear film velocities of 4500 in/sec or 15,000 frames/sec. In order to do this the supply reel motor must be able to rotate at speeds up to 4500 rads/sec or 42,900 rev/min. This means that the back electromotive force (BEMF) constant must be small if the supply voltage is to be a reasonable value. In this case the supply voltage was picked to be 200 volts during the initial camera development. Using the rule of thumb that the maximum speed is the supply voltage divided by the BEMF constant, the maximum BEMF constant allowable is 0.044 volts/rad/sec. Using the relationship that in metric units the BEMF constant and the motor torque constant are equal the maximum torque constant is 6.29 oz-in/amp. The

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problem here is that to attain high speeds the BEMF must be low, but to get to speed as fast as possible the torque constant needs to be as high as possible. The motor specification sheets of several motor manufacturers were examined and the final selection for camera development and testing has a BEMF constant of 0.03342 and a torque constant of 3.68. The complete motor specifications are listed in Table II. This motor was chosen because it had a BEMF constant that fit the speed requirements and a good torque constant compared to other motors. Also its design speed was closer to the desired speed than many others.

```
+---------------------------------------------------------------+
|                                                               |
|                          TABLE II                             |
|                     MOTOR SPECIFICATIONS                      |
|                                                               |
|   TORQUE/AMP                      3.68       oz-in            |
|   BACK EMF                        0.03342    Volts/rad/sec    |
|   TERMINAL RESISTANCE             0.4        ohms             |
|   MOTOR INERTIA                   0.006      oz-in-sec        |
|   ARMATURE INDUCTANCE           < 100        H                |
|   DAMPING TORQUE                  0.00229    oz-in/rad/sec    |
|   MAXIMUM POWER                   0.23       Hp               |
|   MAXIMUM SPEED                   10,000     RPM              |
|                                                               |
+---------------------------------------------------------------+
```

C. SUPPLY REEL

The development of the camera model was an orderly process of design, modify, and test. As each new element was added, the camera program was modified and then tests were run to determine if the progress was satisfactory. In this way problems could be isolated into design and programming problems and it also gave a continually expanding base of good information to work from.

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From the equations of Chapter 2 a model of the supply
reel motor, inertial load, and torque load was created. This
model was then tested to see if it would reach the desired
speed in a time that would make the camera worthwhile. At
this stage the tension on the film was assumed to be
constant and the effect of the film tension on supply reel
acceleration was investigated.

The simulation showed that as tension increased the
supply reel reached design speed faster (Figure 3.1). When
run in an open loop configuration the supply reel took 0.39
sec to reach design speed of 4500 in/sec with 0 oz of
tension and 0.24 sec with 320 oz (20 lbs) of tension on the
film. In the first case 76 feet of film were required and in
the second case 47 feet of film were used during accelera-
tion. This shows that the system can reach design speed in
less than 50 feet of film which is one of the design goals.

The next stage was to close the speed loop and run the
same tests. Here three different tensions were used and the
results are listed in Table III. The time to reach design

TABLE III

CLOSED LOOP SPEED CONTROL OF THE SUPPLY REEL

TIME TO REACH 4500 in/sec	TENSION APPLIED (lb)	FEET OF FILM USED
0.40	0.0	80.0
0.30	10.0	59.0
0.24	20.0	47.0

speed is almost the same as the open loop case, and the
amount of film used up is approximately the same. There was

31
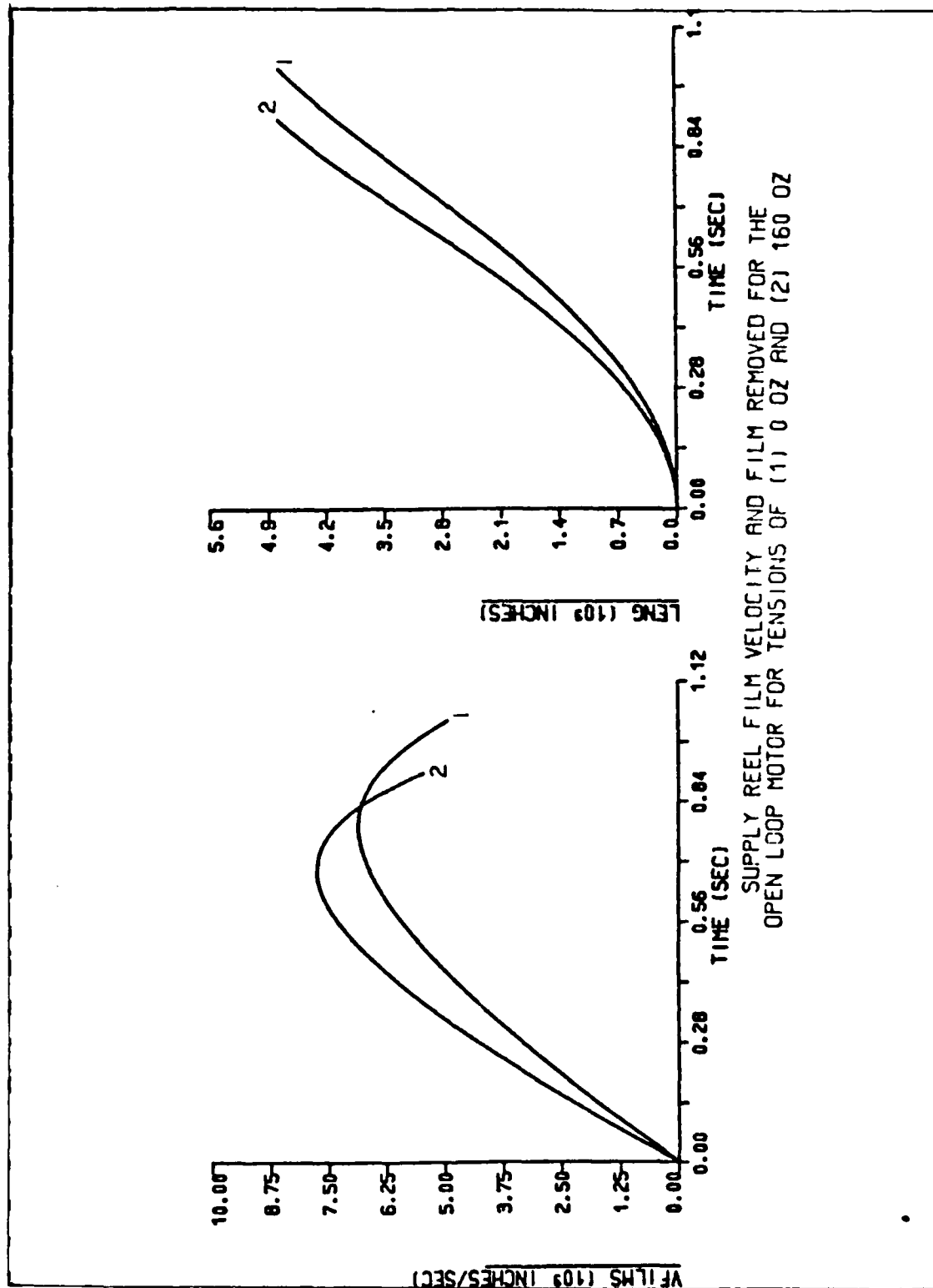
Figure 3.1   Open loop Trials

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no overshoot and the steady state error was 0.1 in/sec. From these results it is evident that even higher tensions would work better. The use of 20 lbs (320 oz.) as a maximum tension is to keep the tension below the value that would break the film. Figures 3.2, 3.3, and 3.4 show the results in Table III graphically.

All of the tests were run under the assumption that a dual power supply was available. Since the camera is to be run from a pulse width modulated power supply, this is the next logical addition to the program. The speed loop response of the motor was indentical for 0 and 10 lbs of tension, but at 20 lbs of tension a problem arose. Because there is no negative power supply to electrically brake the motor and oppose the load torque, the motor overshoots by 780 in/sec and doesn't reach steady state until 0.75 sec. This means that 239 feet of film are wasted in getting to steady state speed. The long settling time is caused by the fact that load torque decreases as a function of the reel radius while the force generated due to the BEMF voltage, the only opposing force, is relatively constant. Therefore, until the radius decreases to a point where load torque equals the braking force due to the BEMF voltage, the film speed continues to be excessive (Figure 3.5). Through simulation it was found that this problem exists if a tension of more than 17 lbs is applied to the supply reel.

At this point the results show that a maximum tension of 17 lbs can be applied to the supply reel. The ideal speed loop works very well, and the speed is controlled to within 0.1 frames per second. The camera reaches steady state speed in approximately 0.3 seconds, and uses up 60 feet of film during acceleration.

33
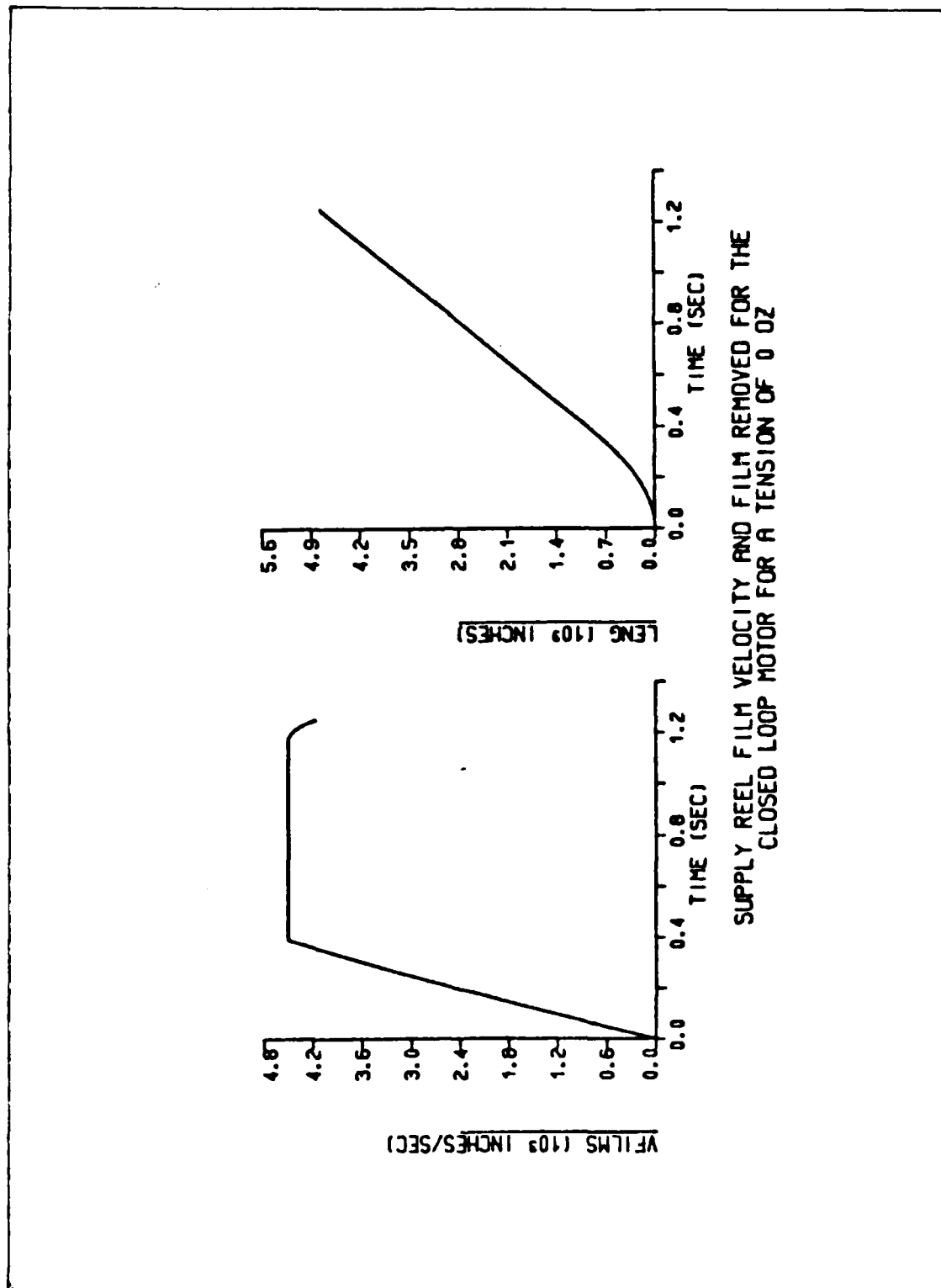
Figure 3.2   Closed Loop Supply Reel, Tension = 0 oz

34
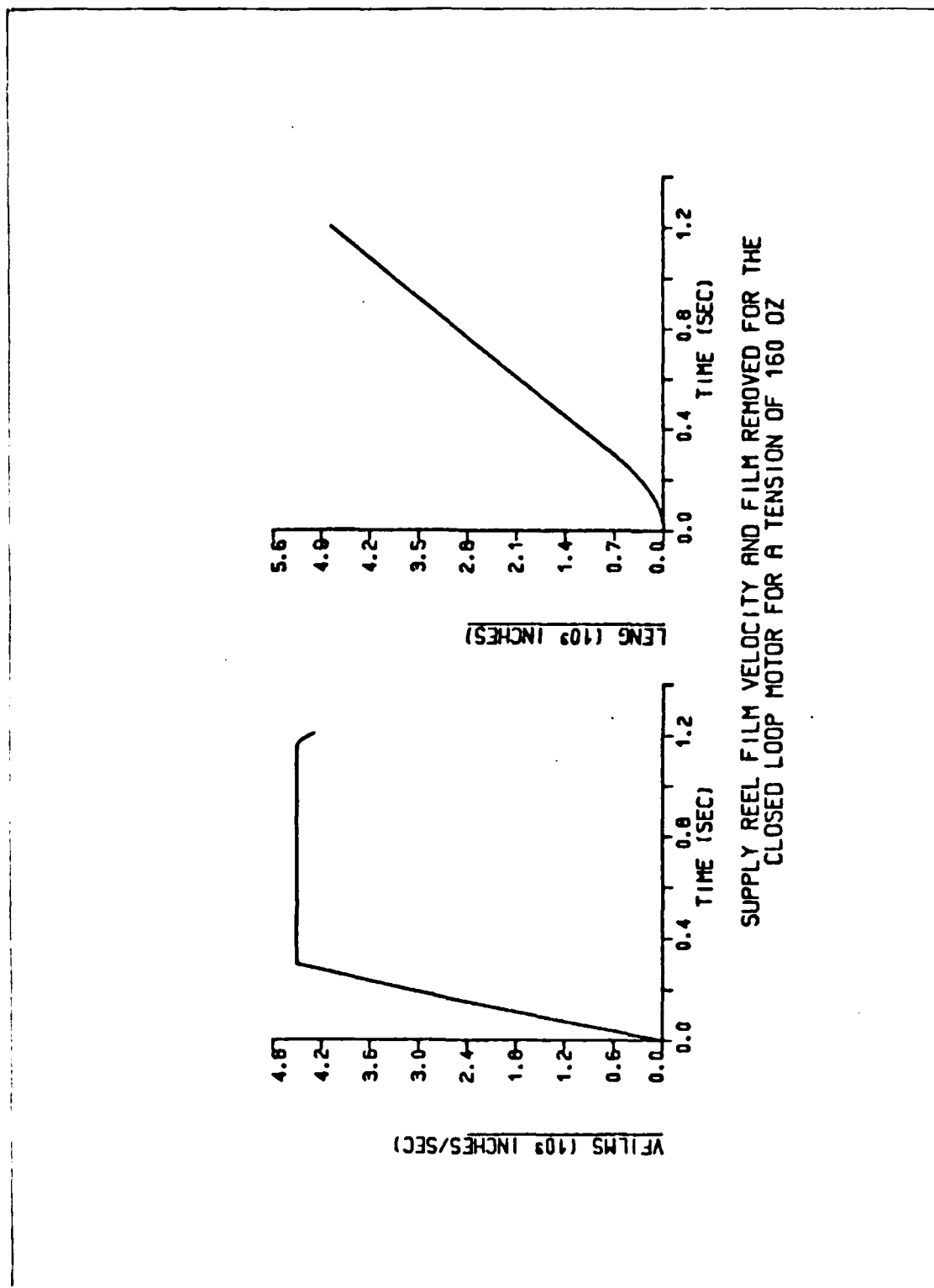
Figure 3.3   Closed Loop Supply Reel, Tension = 160 oz
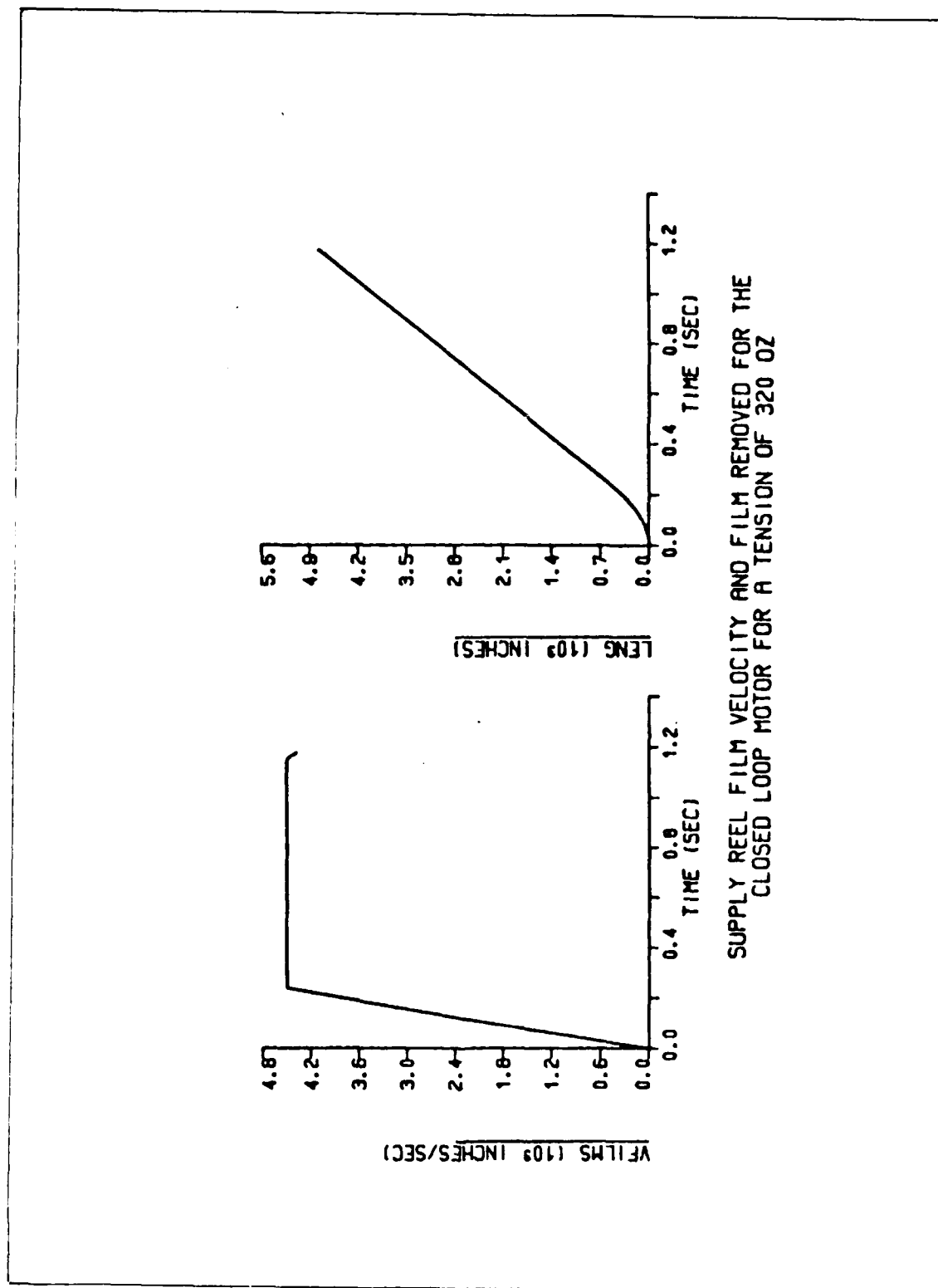
Figure 3.4   Closed Loop Supply Reel, Tension = 320 oz

36
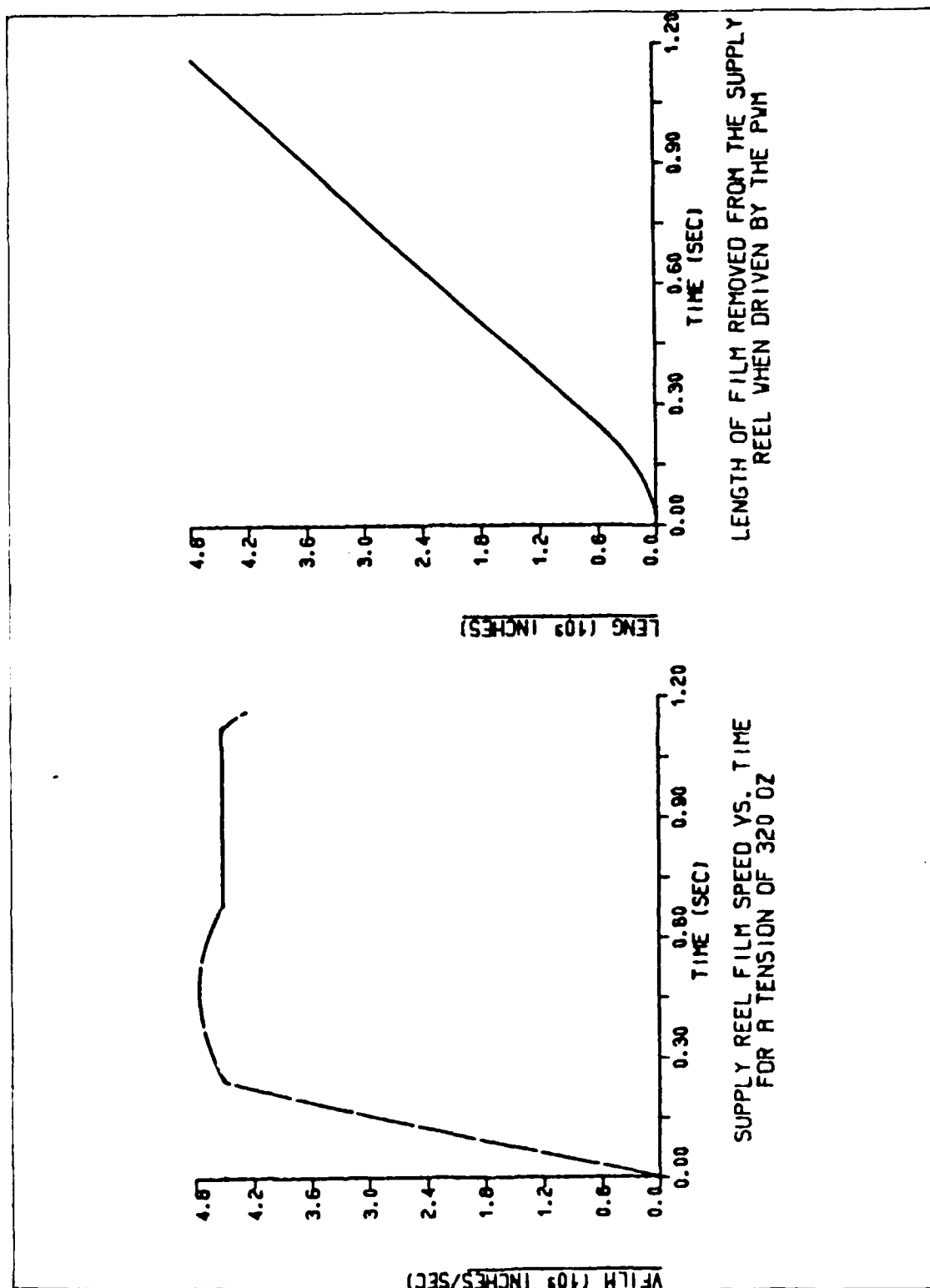
Figure 3.5   Supply Reel Film Speed when Driven by a
Pulse Width Modulated Power Supply

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D. TAKE UP REEL

The program to simulate the take up reel is the same as the supply reel program except that the reel radius increases and the load torque opposes the motor instead of aiding it. Because of the work already done on the supply reel, the take up reel testing started with an ideal speed loop.

The simulations showed that the take up reel is not as affected by load tension during acceleration. This is due to the fact that the radius is initially very small. The results listed in Table IV show a change in time of 0.07 sec for the take up reel while a similar change in tension caused a change of 0.16 sec in the settling time of the supply reel. Figure 3.6 shows a simulation run of the take up reel. One other difference to note is the absence of the droop at the end of the run. Even though the load torque is at its maximum the motor is at its lowest required speed. Therefore there is more than enough power to overcome the load torque and maintain steady state speed.

TABLE IV

CLOSED LOOP SPEED CONTROL OF THE TAKE UP REEL

TIME TO REACH 4500 in/sec	TENSION APPLIED (lb)	FEET OF FILM USED
0.22	0.0	41.5
0.25	10.0	47.7
0.29	20.0	56.1

The next stage is to look at the effects of replacing the bipolar power supply with a pulse width modulated power
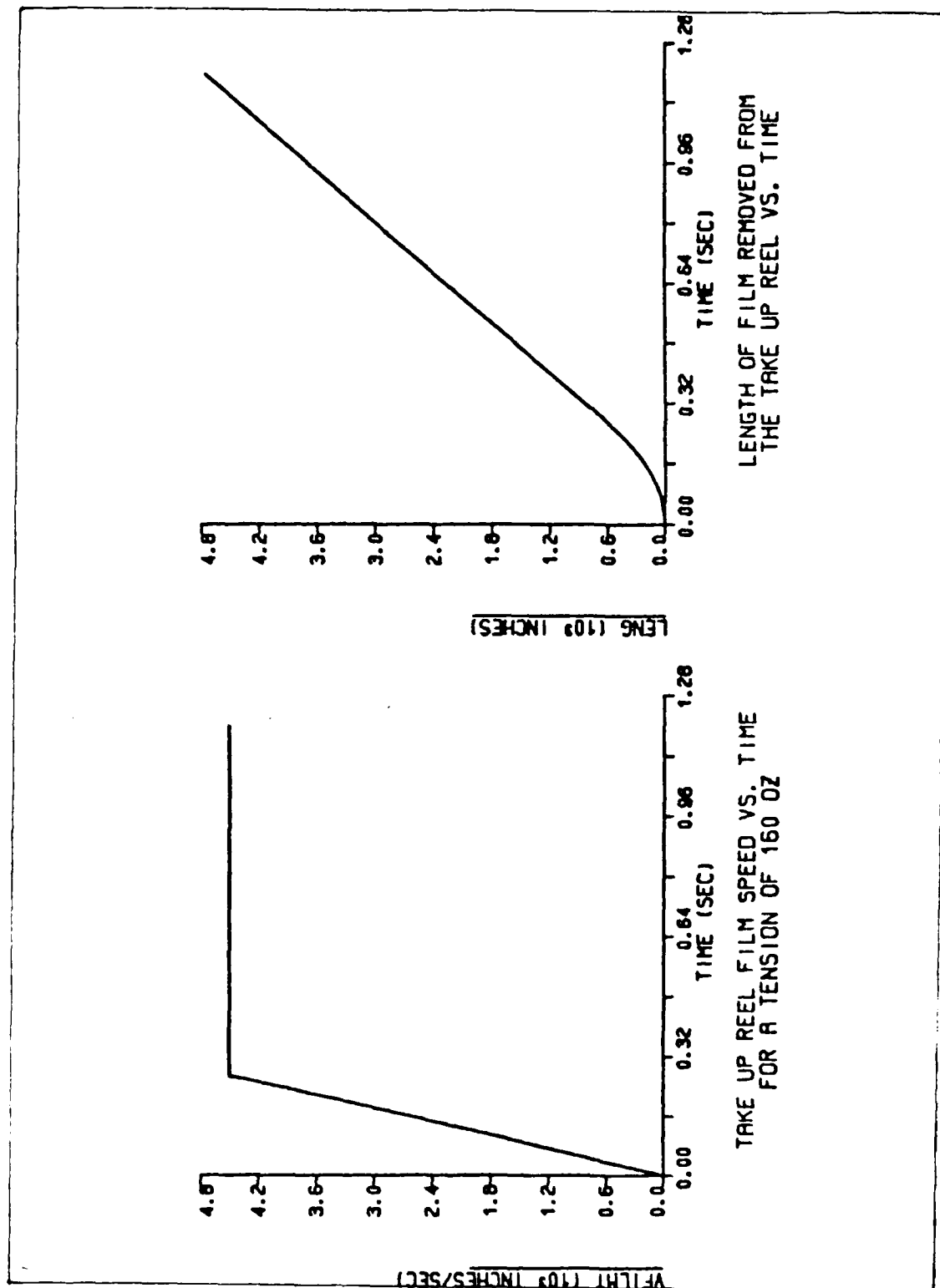
Figure 3.6   Closed Loop Take Up Reel Film Speed,
Tension = 160 oz

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supply. Here the problems of the supply reel do not crop up. The only effect is a slightly longer time to reach steady state and a comparatively larger amount of film is used. The take up reel takes 0.03 seconds longer to reach steady state and 6 more feet of film are used. The simulation using 10 lbs of tension is shown in Figure 3.7.

E. COMBINING BOTH REELS

When the two reel programs are combined to form a complete camera, the question of the amount of film in the loop between the two reels becomes important. If the supply reel accelerates faster than the take up reel then an excess of film will be accumulated. If the reverse is true then all the excess will be removed from the loop and the two reels could stretch the film to the breaking point. Both of these situations are detrimental if allowed to go to the extreme.

Initial testing was done by applying a step command to both motors. The tension was 15 lbs to both reels and the results (Figure 3.8) show that over 80 inches of film were accumulated in the loop due to the supply reel accelerating faster than the take up reel. If the tension is lowered the situation becomes less severe, but still it is excessive. With careful work the exact value of tension that allows both motors to accelerate at the same rate can be found, but this value will only work for that ordered speed. For each speed a new value of tension would have to be found.

This problem can be overcome by taking the actual speed of one reel and use it as the reference signal for the other reel. In this way the two reels operate in a master-slave relationship. This will work as long as the slave can accelerate as fast or faster than the master. Since the supply reel has the largest inertial load to accelerate it was decided to start with this motor as the master. Since the
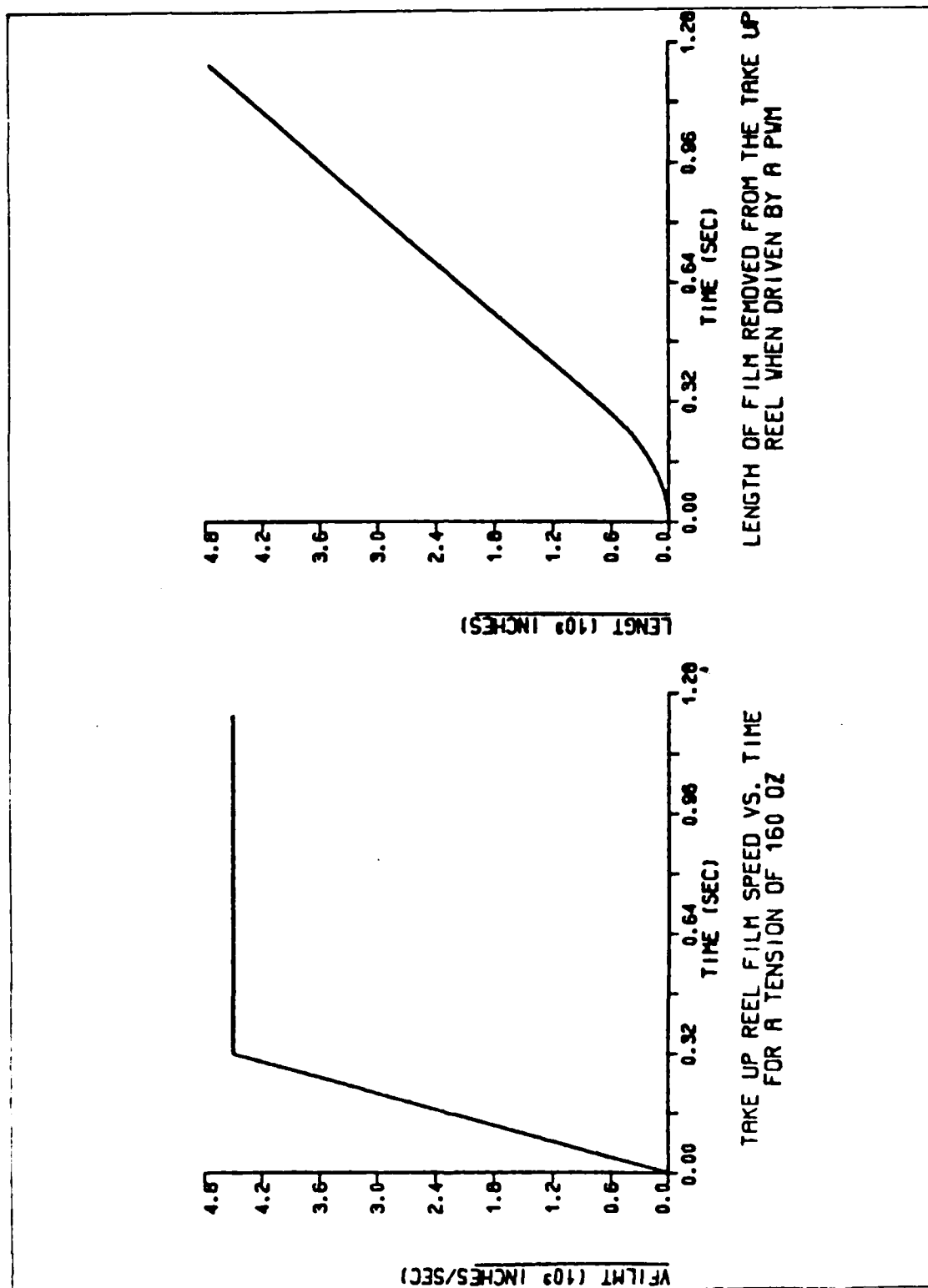
Figure 3.7   Take Up Reel Film Speed when Driven by a
Pulse Width Modulated Power Supply

41
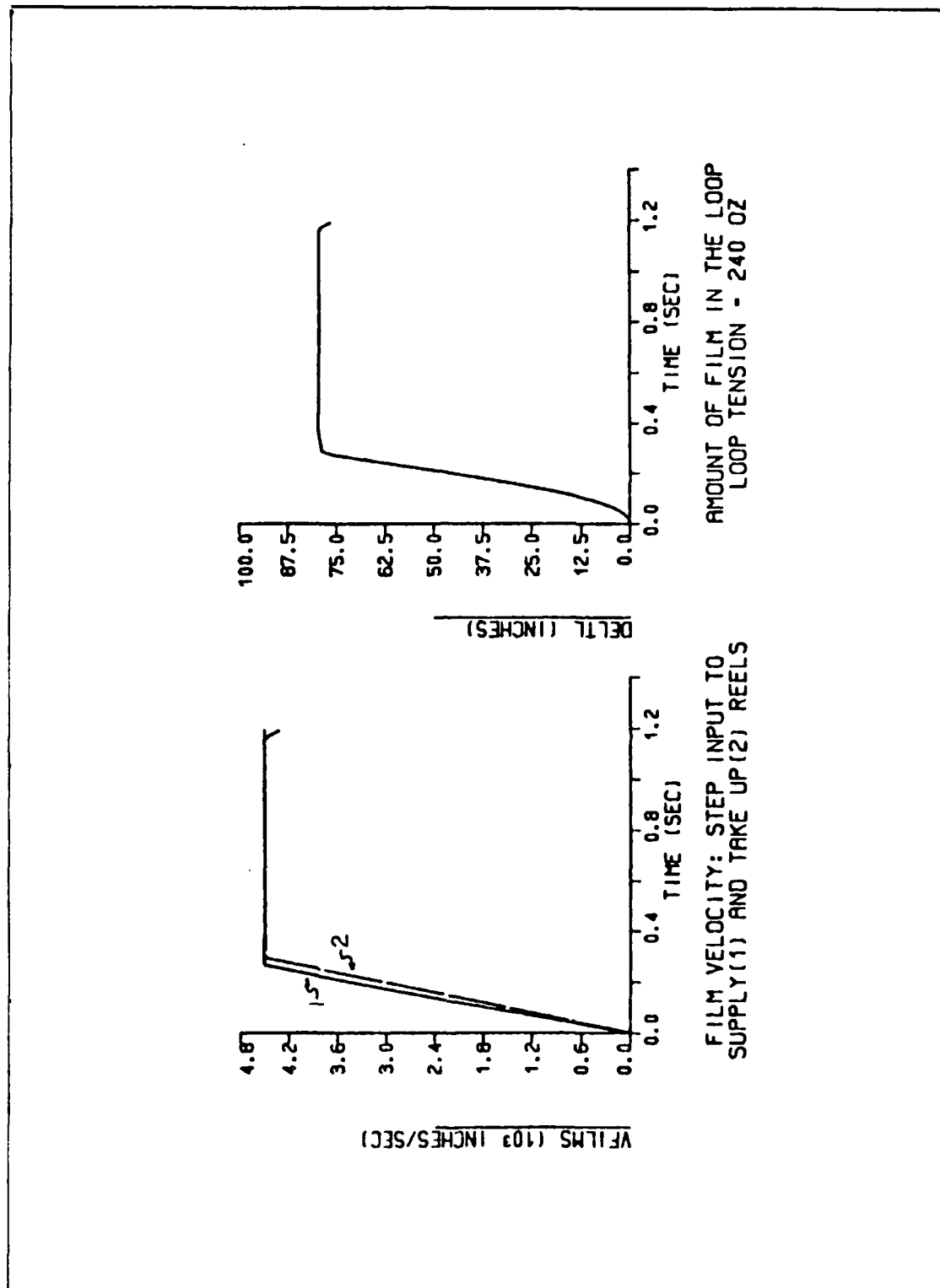
Figure 3.8   Two Motor Camera, Step Input to both Motors

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more tension applied the quicker the supply reel acceler-
ates, the initial simulation used 15 lbs (Figure 3.9). The
results showed that with 15 lbs of tension the supply reel
accelerates faster than the take up reel and an excess of
79.6 inches of film results. Another run using 10 lbs was
conducted (Figure 3.10) and the results were excellent. At
initial start up the supply reel is slightly faster and a
small excess of film (0.25 in) develops, but this is all and
at steady state no additional film is added or subtracted
from the loop. At the very end when the supply reel speed
droops the situation reverses, but the final result is only
one quarter inch from the initial starting point of zero.
This shows that for a speed of 15,000 frames/second the two
motors can be controlled so that the amount of film added to
or removed from the loop is kept to a reasonable value.
This will become clearer when the tension loop is added.

F. TENSION LOOP

From all the results so far it is evident that the
tension on the film is important. The film tension needs to
be as high as possible to accelerate the supply reel as fast
as possible and yet the amount of change in the film in the
loop must be kept to a minimum. To achieve this the dancer
and spring described in Chapter Two is used. This provides a
place to take up the slack or provide the shortage when the
two reels are accelerating or decelerating. The dancer
assembly also provides a place to measure the film tension.
This signal will later be used to control the tension in the
film.

The dancer can move 2 inches from stop to stop.
Therefore to take care of excess film or be able to make up
for a shortage the dancer should start out at the mid point
of travel. Initial simulation used a spring with a constant

43
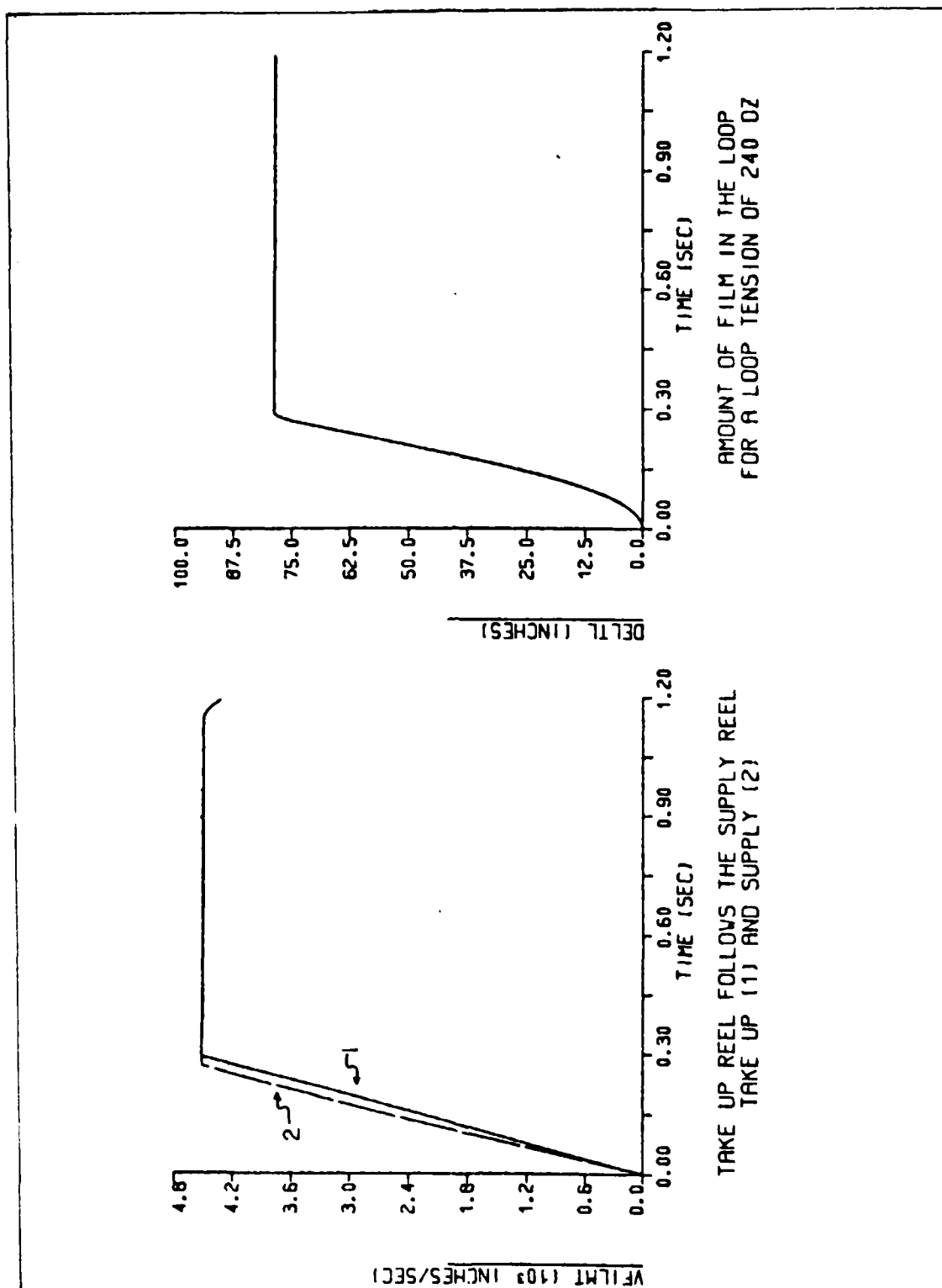
Figure 3.9   Take Up Follows Supply, Tension = 240 oz

44
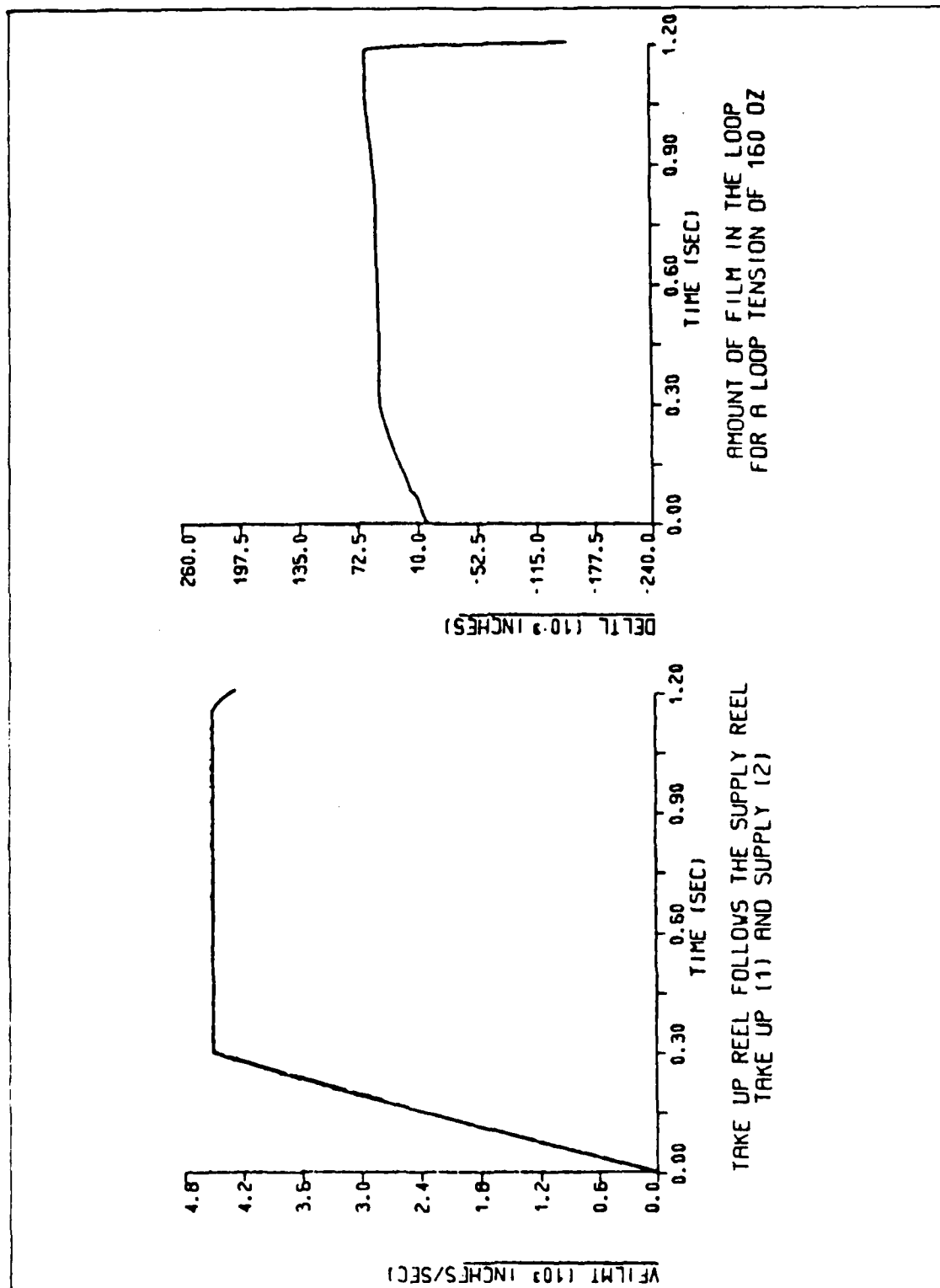
Figure 3.10   Take Up Follows Supply, Tension = 160 oz

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of 10 lbs or 160 oz per inch of travel. The damping coeffi-
cient was 10 oz per inch per second. With these values, for
an initial tension of 10 lbs, the spring must be at the 2
inch position. The dancer can move ± 1 inch from this
position.

The initial testing did not involve any tension feed-
back. This system was tensioned to the right amount and then
started. Three different values of tension (10 lbs, 12 lbs,
and 15 lbs) were used and in each case the system response
was similar. Since the take up reel is following the supply
reel an excess of film is developed (Figure 3.11). This
causes the dancer to move to take up the slack and the loop
tension to decrease (Figure 3.12). As the tension decreases
the take up reel can accelerate as fast as the supply reel,
the dancer motion slows down, and the loop tension steadies
out. The differences in the three runs lies in the steady
state values achieved. Table V contains the steady state
values. The simulations show good results in all three
cases, but as the tension increases the amount of dancer
travel increases. This also shows that even though 15 lbs of
tension was unacceptable before, it now gives good results.
Also the movement of the dancer takes up the excess film and
provides a reservoir of film when the situation reverses.

Up to this point the armature current of the motors was
allowed to be as large as needed to drive the film at the
desired speed. Figure 3.13 shows the armature current for
the supply reel when 10 lbs of tension are applied. Here the
current during acceleration is as high as 490 amperes, which
is too much. Therefore a current limiting circuit was placed
on each motor to limit the armature current to 300 amperes.
To see what effect this would have the above simulations for
10 lbs and 15 lbs of tension were rerun. In each case the
acceleration time was longer (0.4 seconds), and the dancer
had to move more to take up the increase in film in the loop
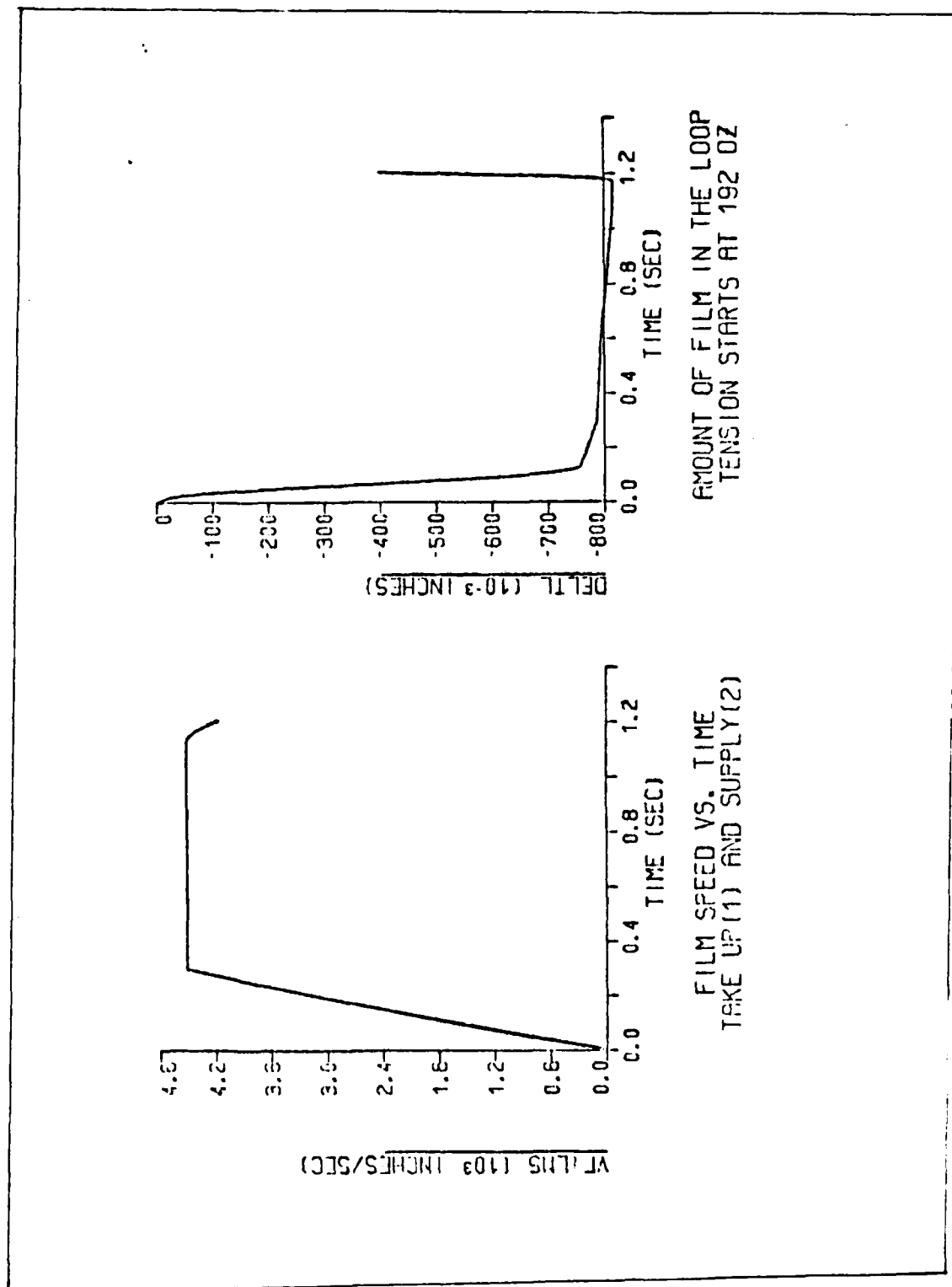
Figure 3.11   Film Speed and Film in the Loop
using Dancer Assembly

47
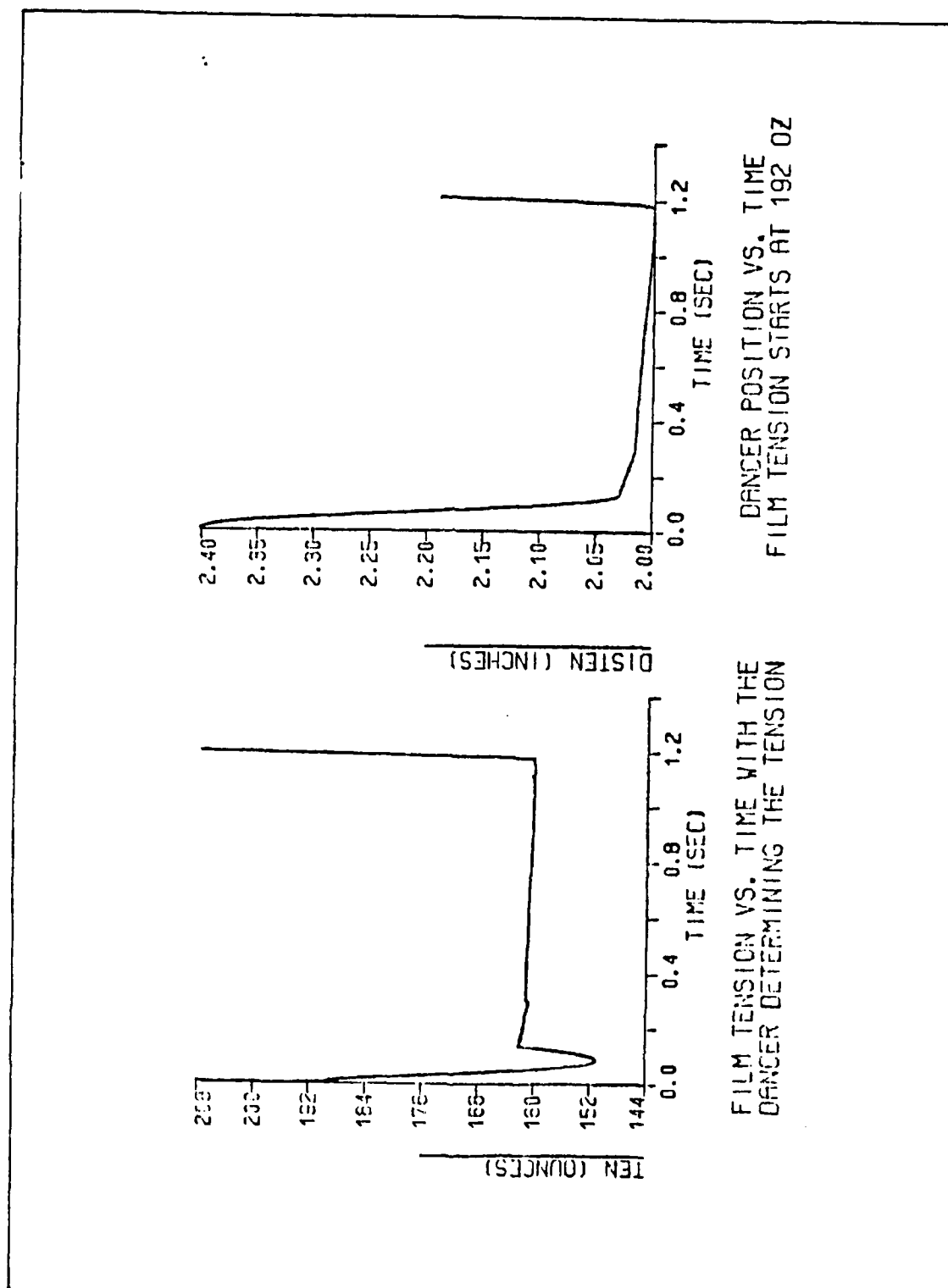
**Figure 3.12   Film Tension and Dancer Position
using Dancer Assembly**

TABLE V

FILM TENSION AND DANCER POSITION

TENSION (oz)		DANCER POSITION (in)		FILM IN LOOP (in)
INITIAL	STEADY STATE	INITIAL	STEADY STATE	
160	158	2.0	1.955	0.09
192	162	2.4	2.025	0.78
240	168	3.0	2.100	1.80

(Figures 3.14, 3.15, and 3.16). However the system performance was still good, speed regulation was excellent, and the steady state values of all parameters, while different, were still within tolerances.

At this point a tension loop was added to control and maintain the film tension at a steady value. There are three possible combinations for the tension loop. The error signal can be fed to the supply reel, the take up reel, or it can be fed to both reels. With the supply reel as the master, sending the error signal to the supply reel alone (Figure 3.17) acts as a bias that keeps the supply reel from reaching the desired speed. Also because the take up reel is so fast it follows the supply reel and keeps the tension from coming into line (Figure 3.18). Sending the error signal to the take up reel alone or to both reels yields almost identical results. The speed regulation and the tension regulation are both good (Figures 3.19 and 3.20).

Since the results were so good, the master-slave relationship was reversed and the take up reel became the master. Again, feeding the error signal to the master reel doesn't work, and applying the error signal to both reels gives the same results as applying it to the slave only.
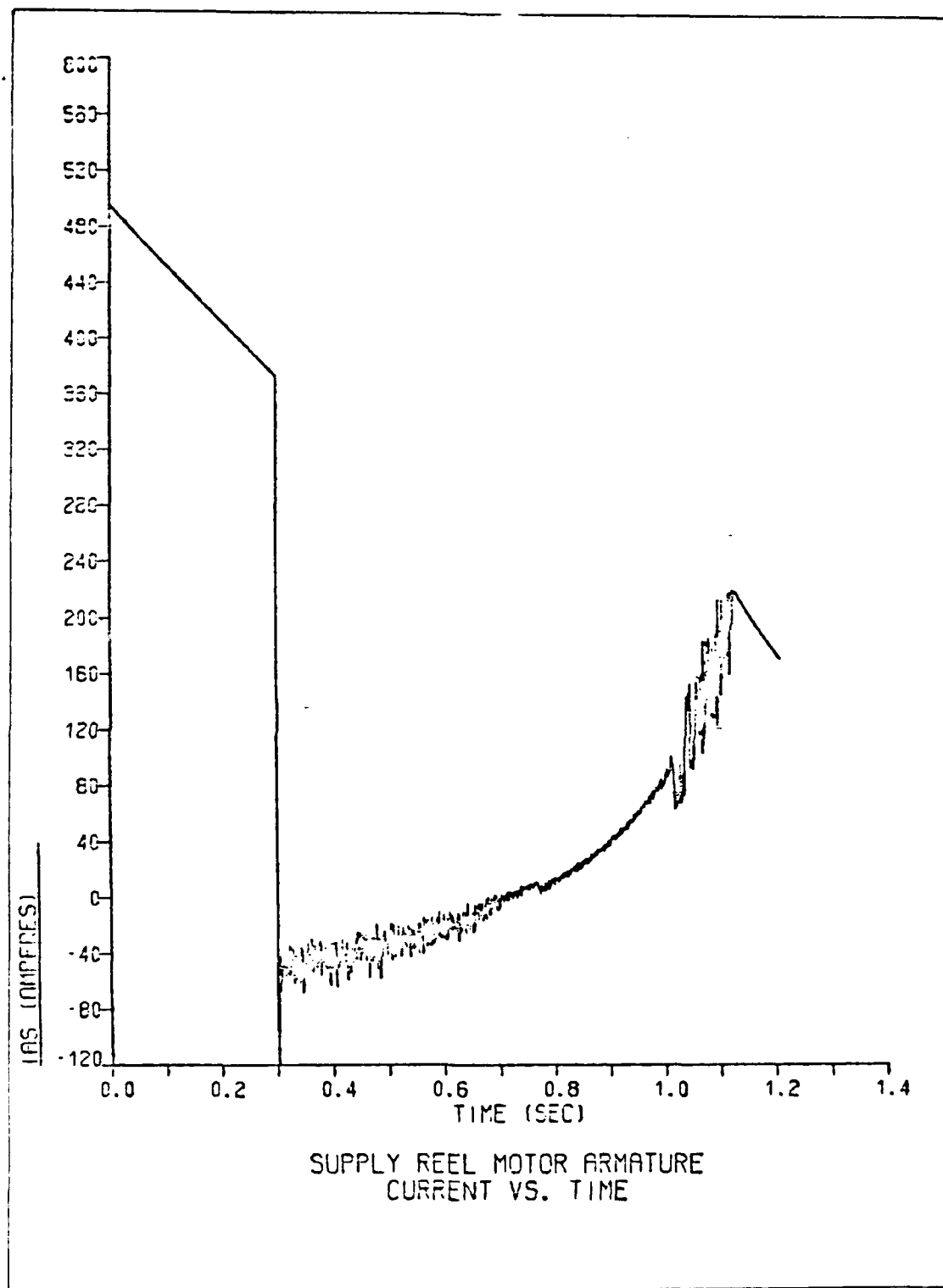
Figure 3.13   Supply Reel Motor Armature Current
without Current Limiting

50
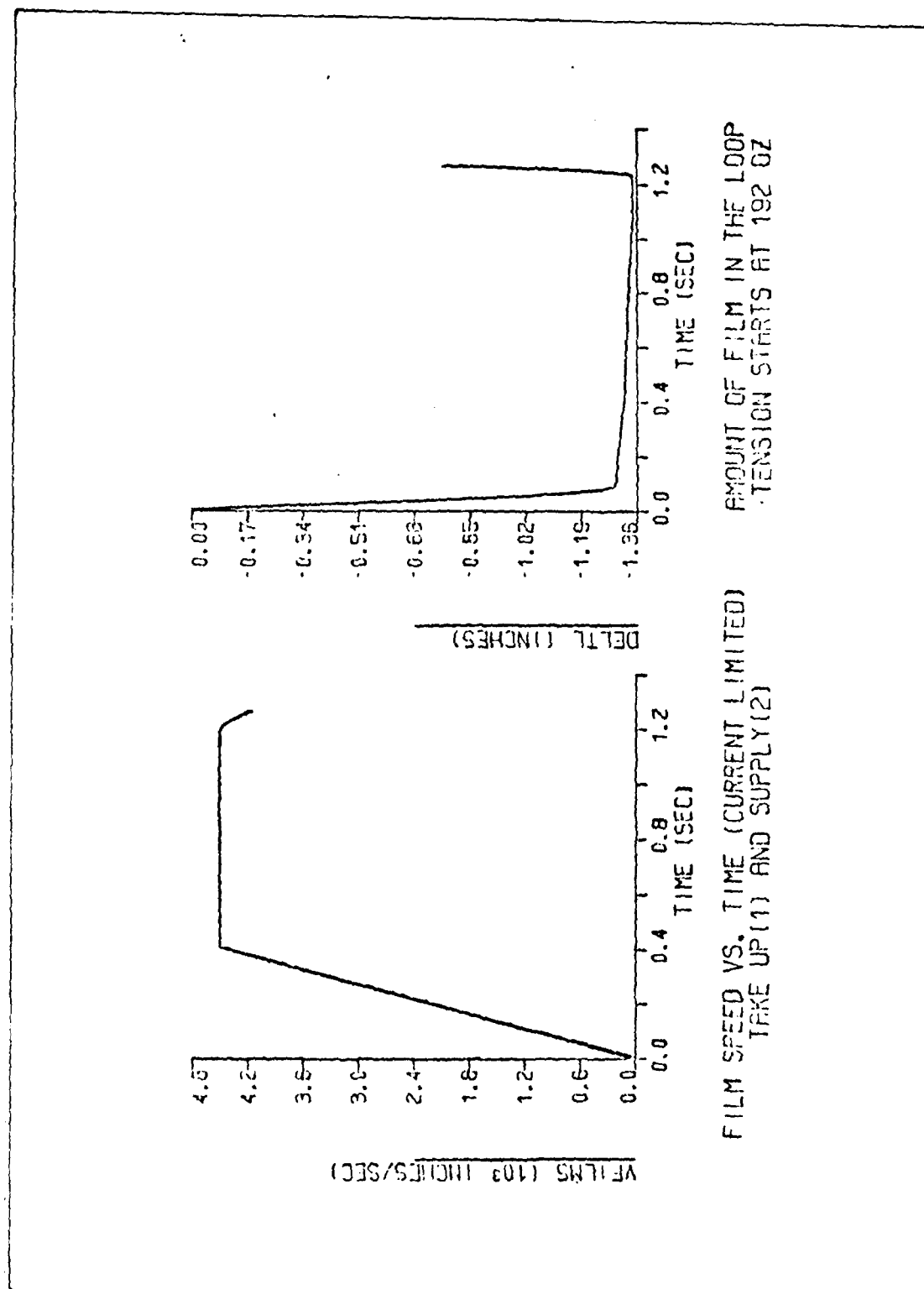
Figure 3.14   Film Speed and Film in the Loop
with Current Limiting

51
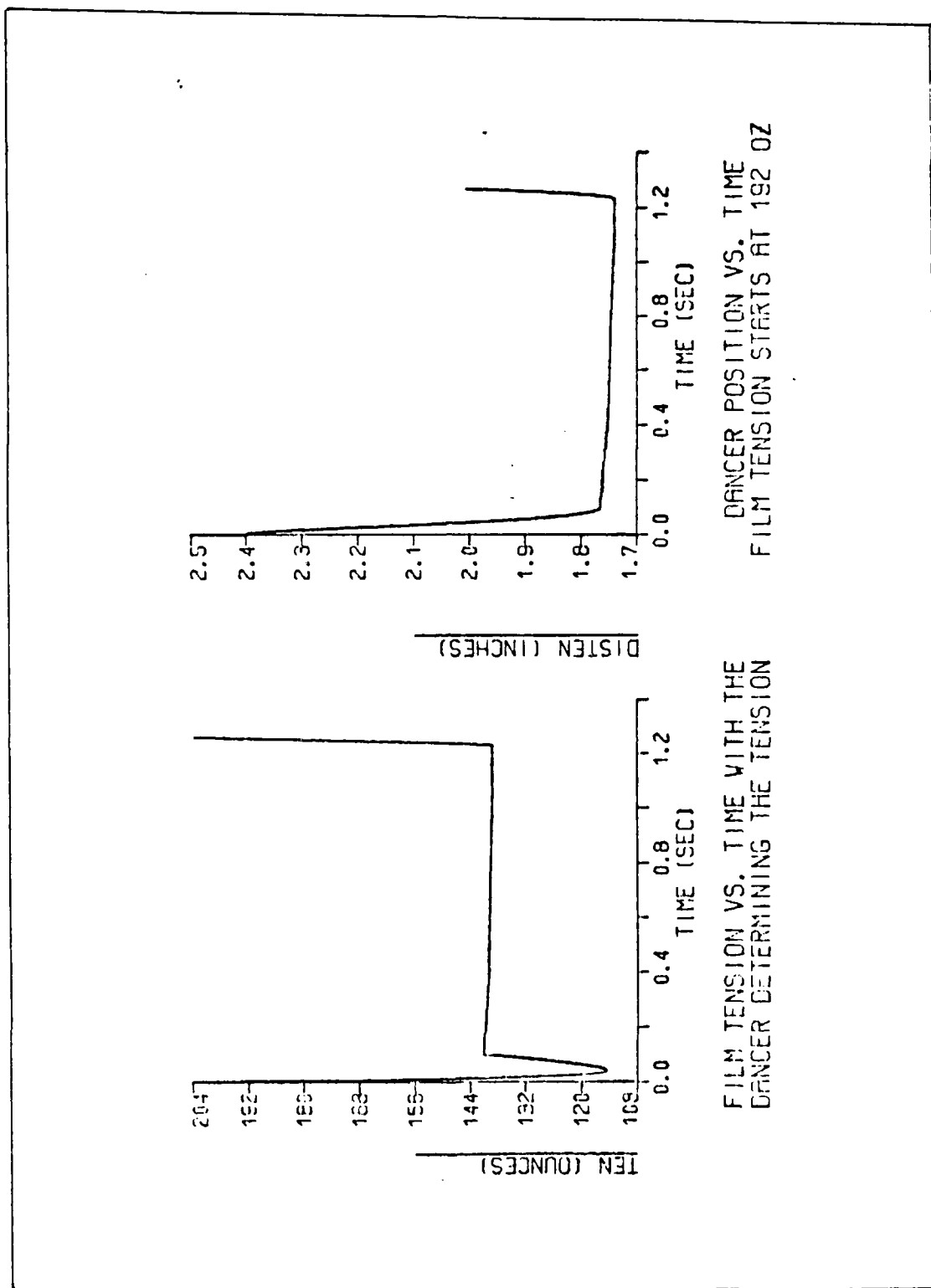
Figure 3.15   Film Tension and Dancer Position with Current Limiting
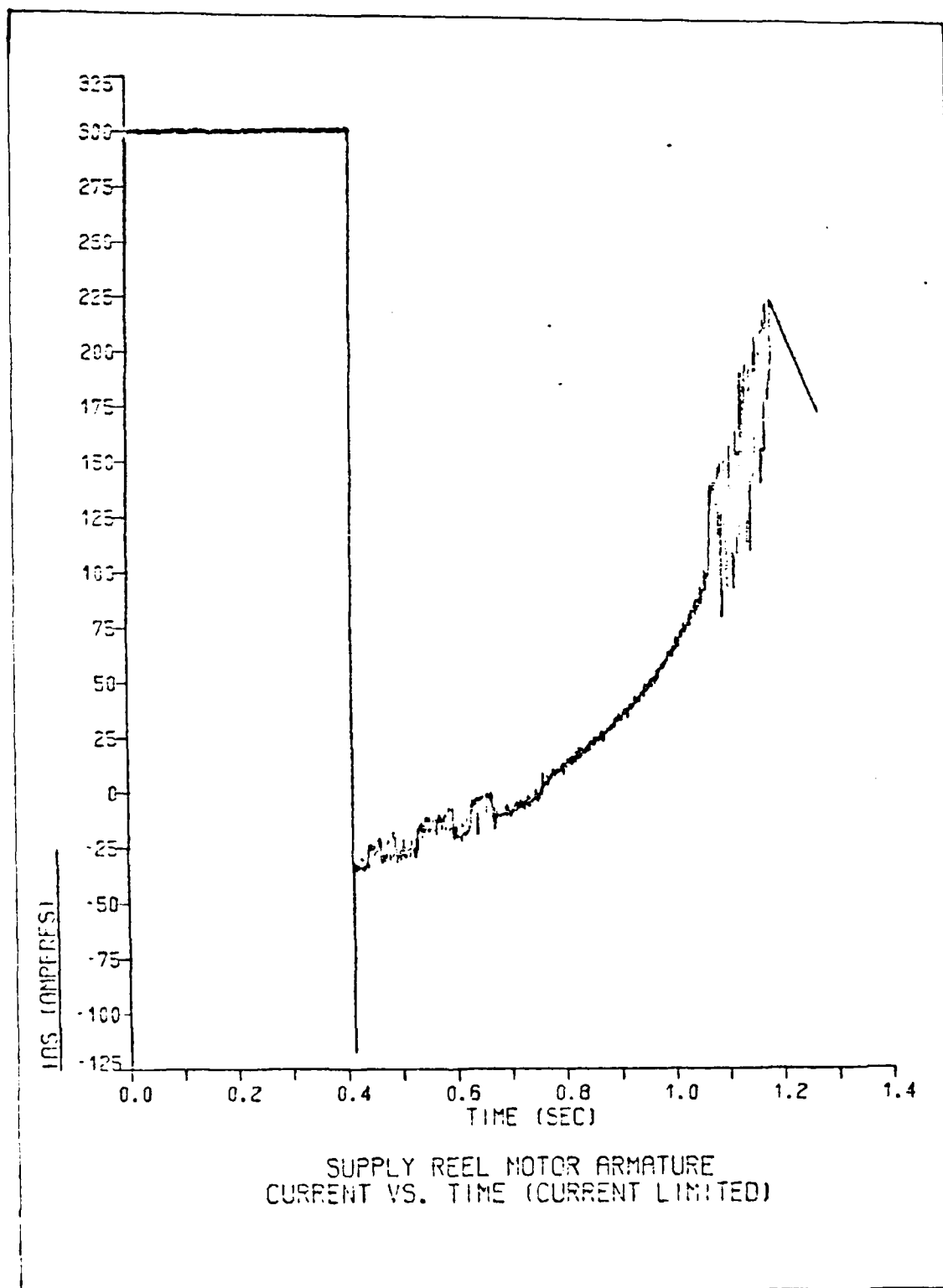
Figure 3.16   Supply Reel Motor Armature Current
with Current Limiting

53
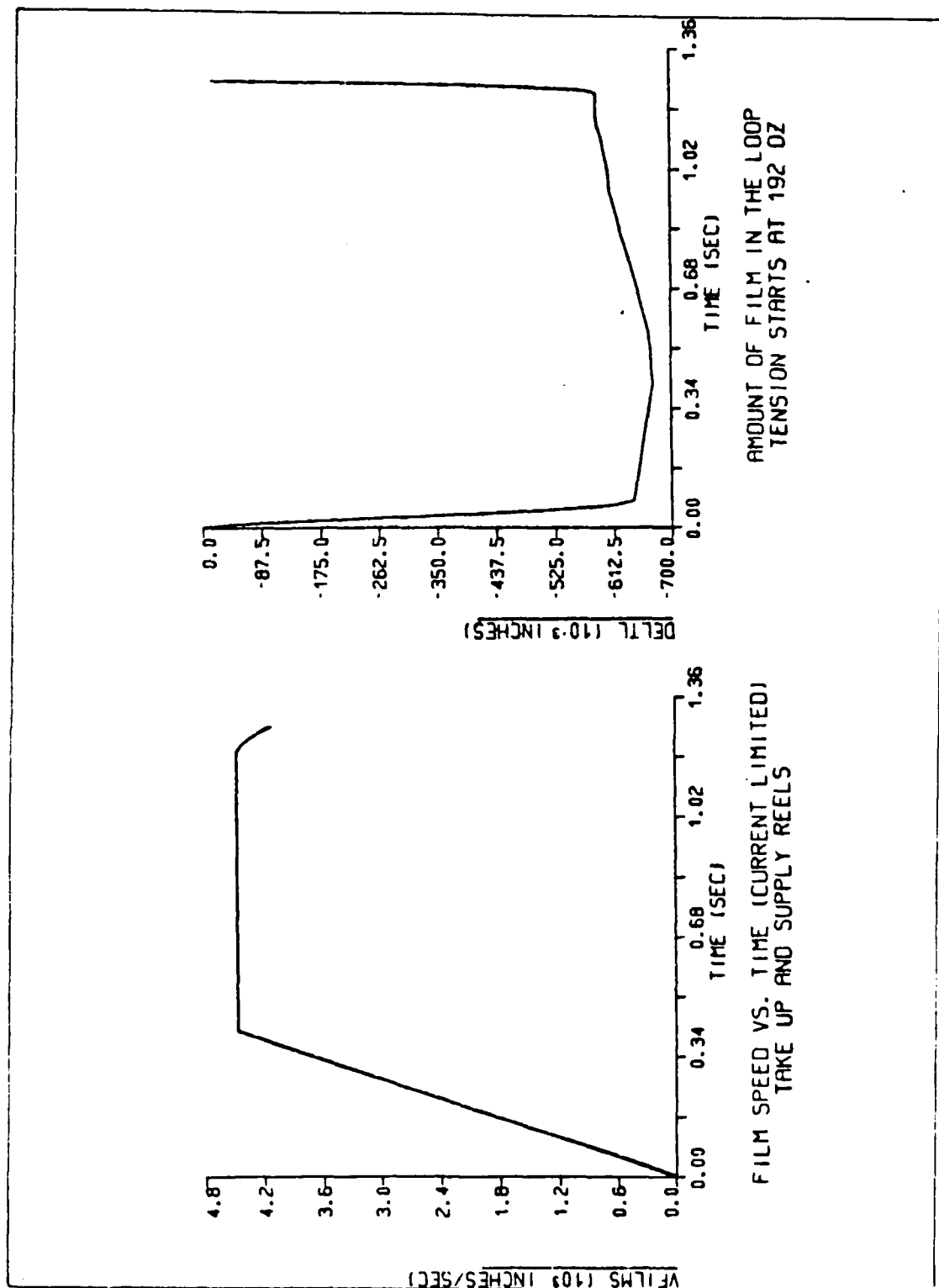
Figure 3.17   Film Speed and Film in the Loop.
Dancer Position Determines the Tension

54
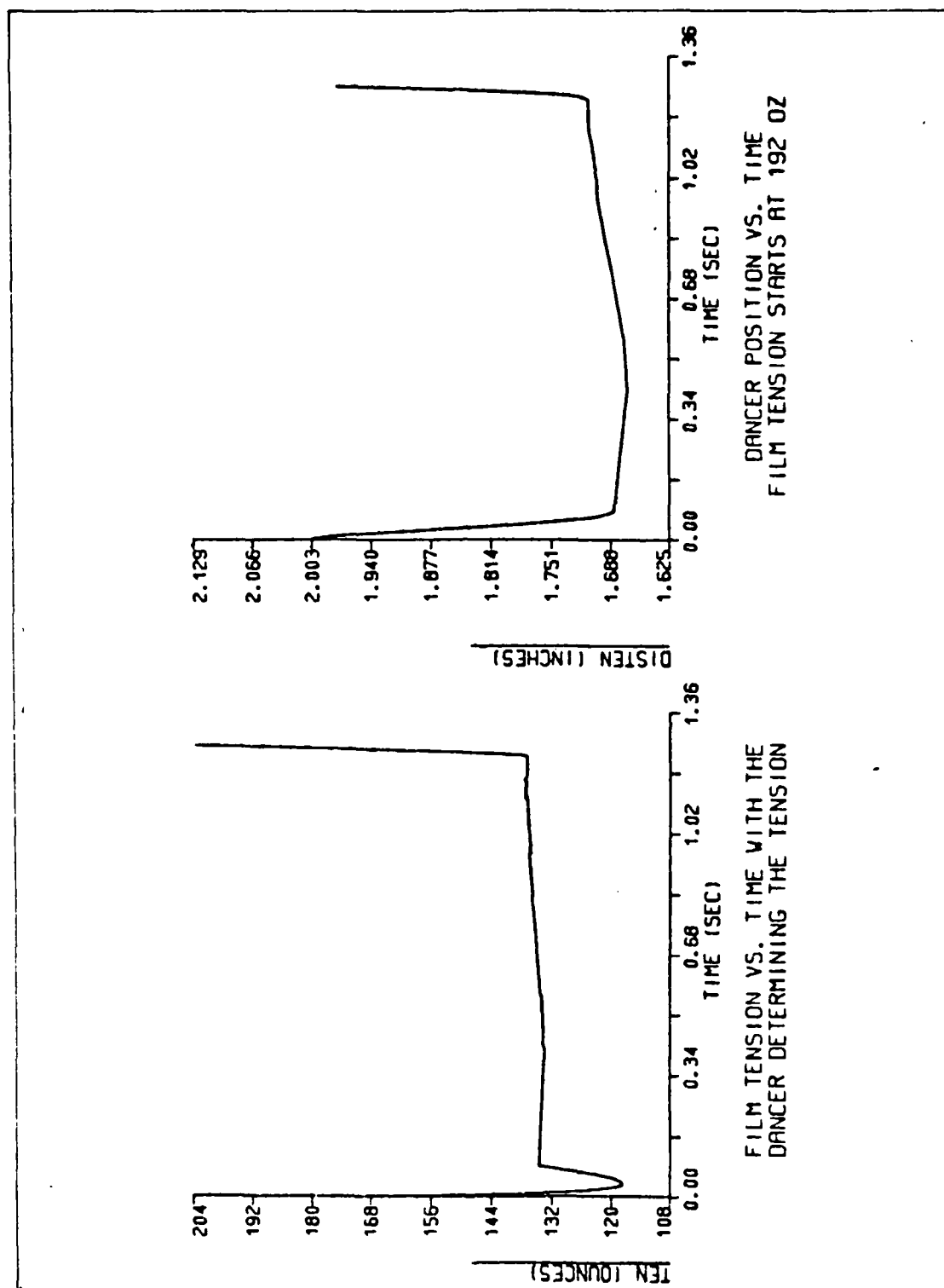
Figure 3.18   Film Tension and Dancer Position.
Dancer Position Determines the Tension

55
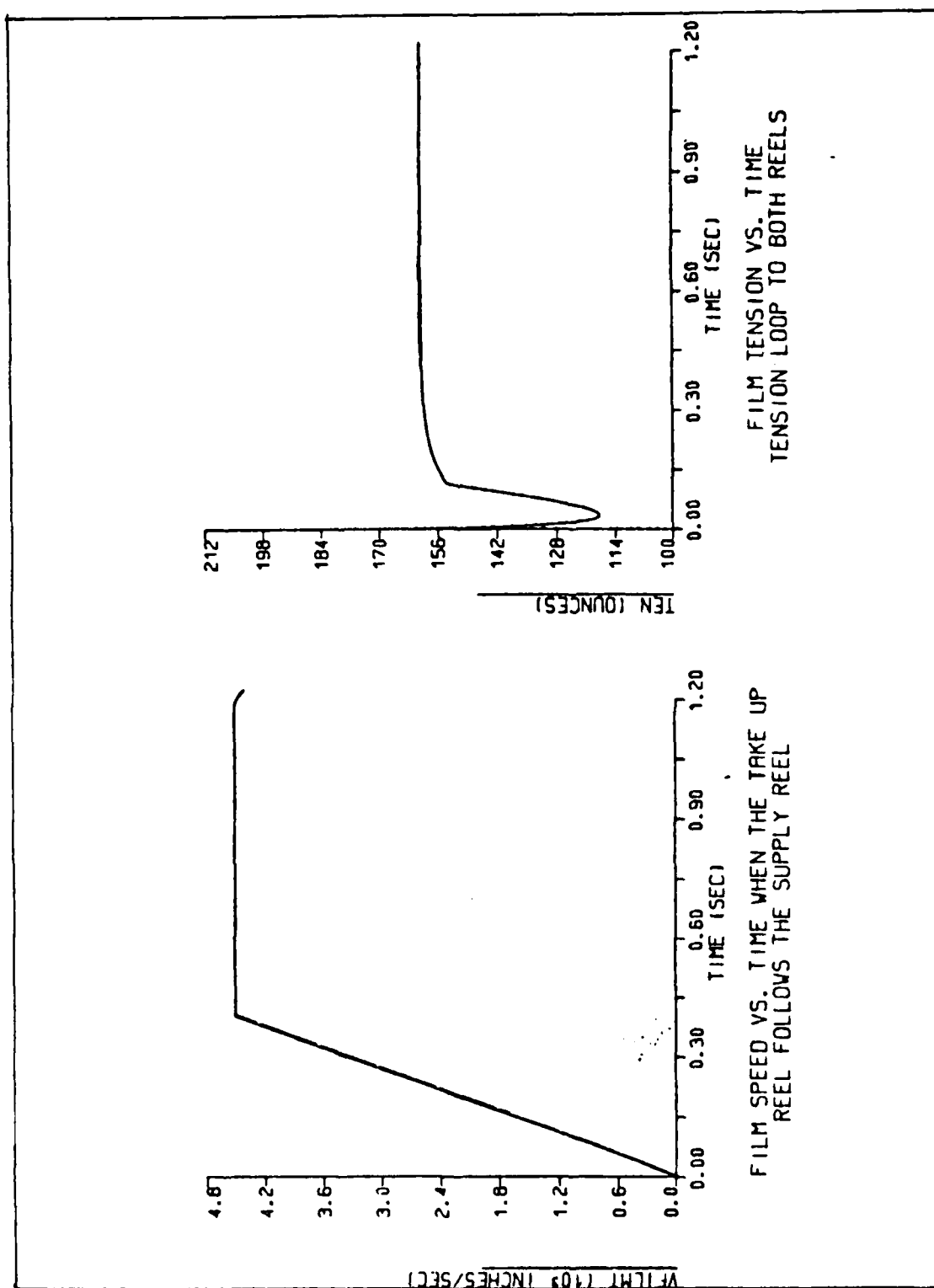
Figure 3.19   Film Speed and Film Tension with
the Tension Loop signal to both Reels

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However, the curve shapes are different. Instead of having a brief dip and then a return to steady state, the tension stays relatively constant until the transition is made from acceleration to steady state speed. Here there is a spike due to a mismatch in how the two motors make the transition. While the tension spike (Figure 3.21) is not excessive, the change in dancer position is more than the one inch allowable. Therefore, at this time it appears as if using the supply reel as the master is the better of the two schemes.

G. SHUTTER ASSEMBLY

The final part to be modeled is the shutter assembly. Because of the inertia and the energy transfer at the shutter, the film is now modeled as two springs. One length of film from the supply reel to the shutter, which includes the dancer assembly, and another length of film from the shutter to the take up reel. The equations and the computer simulation program were discussed in Chapter Two.

Initially, the simulations with shutter assembly included were run with the supply reel as the master and the tension error signal was fed to the take up reel. The output showed a marked drop in regulation of both the film speed and the loop tension (Figures 3.22 - 3.24). Although the amount of clutter hides it, the master reel still has excellent regulation. It is the slave reel (Figure 3.22) and the shutter assembly (Figure 3.24) that have poor regulation. This is especially bad because it is the film speed at the shutter that is the most important. It is also apparent from Figure 3.23 that the system can not regulate the loop tension. In this case no limits are exceeded, but it is not desirable to have a system parameter that will not behave. The apparent reason for this behavior is that using the take up reel to control the tension causes a delay in tension

57
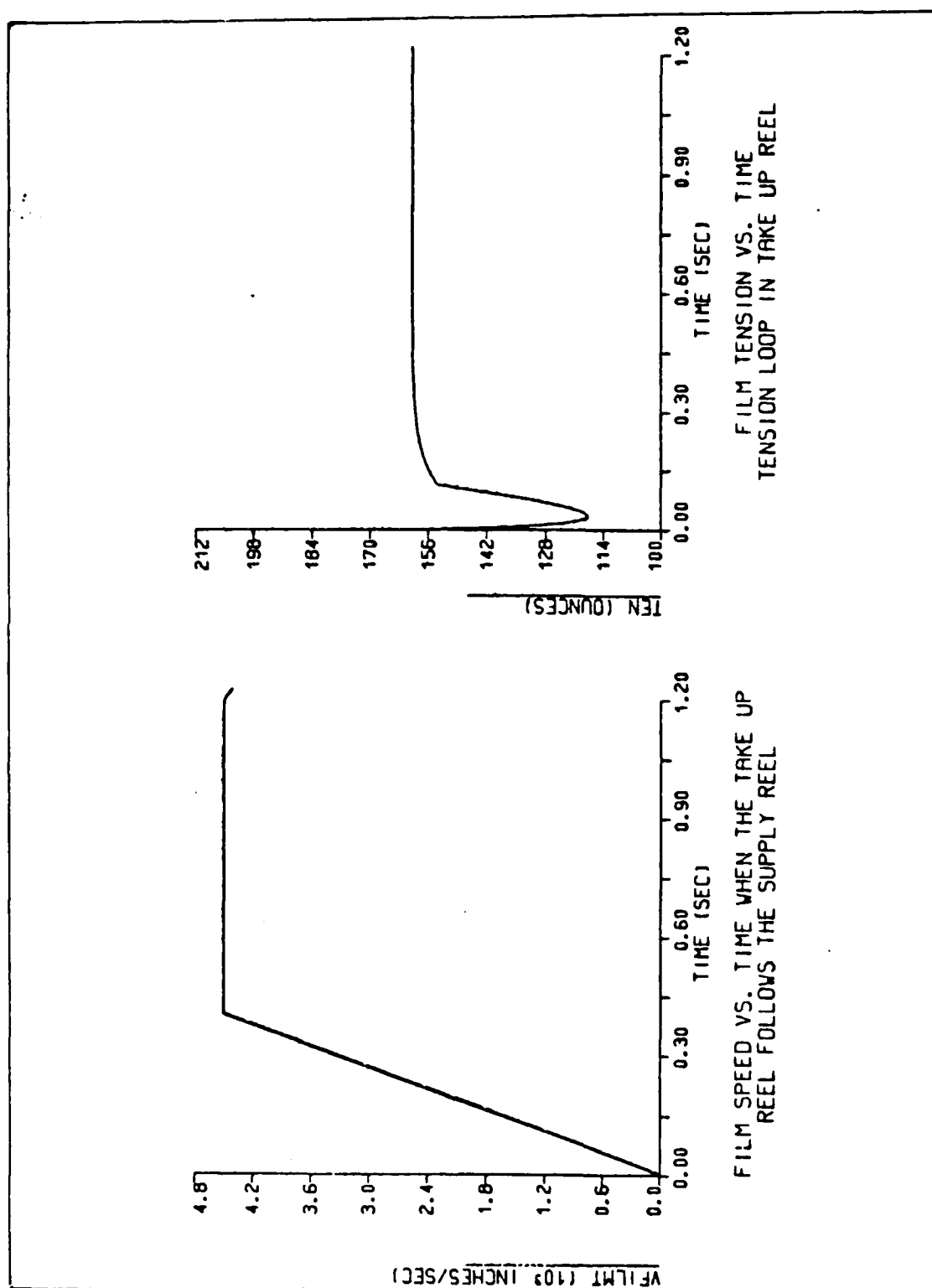
Figure 3.20   Film Speed and Film Tension,
Tension Loop in Take Up Reel

58
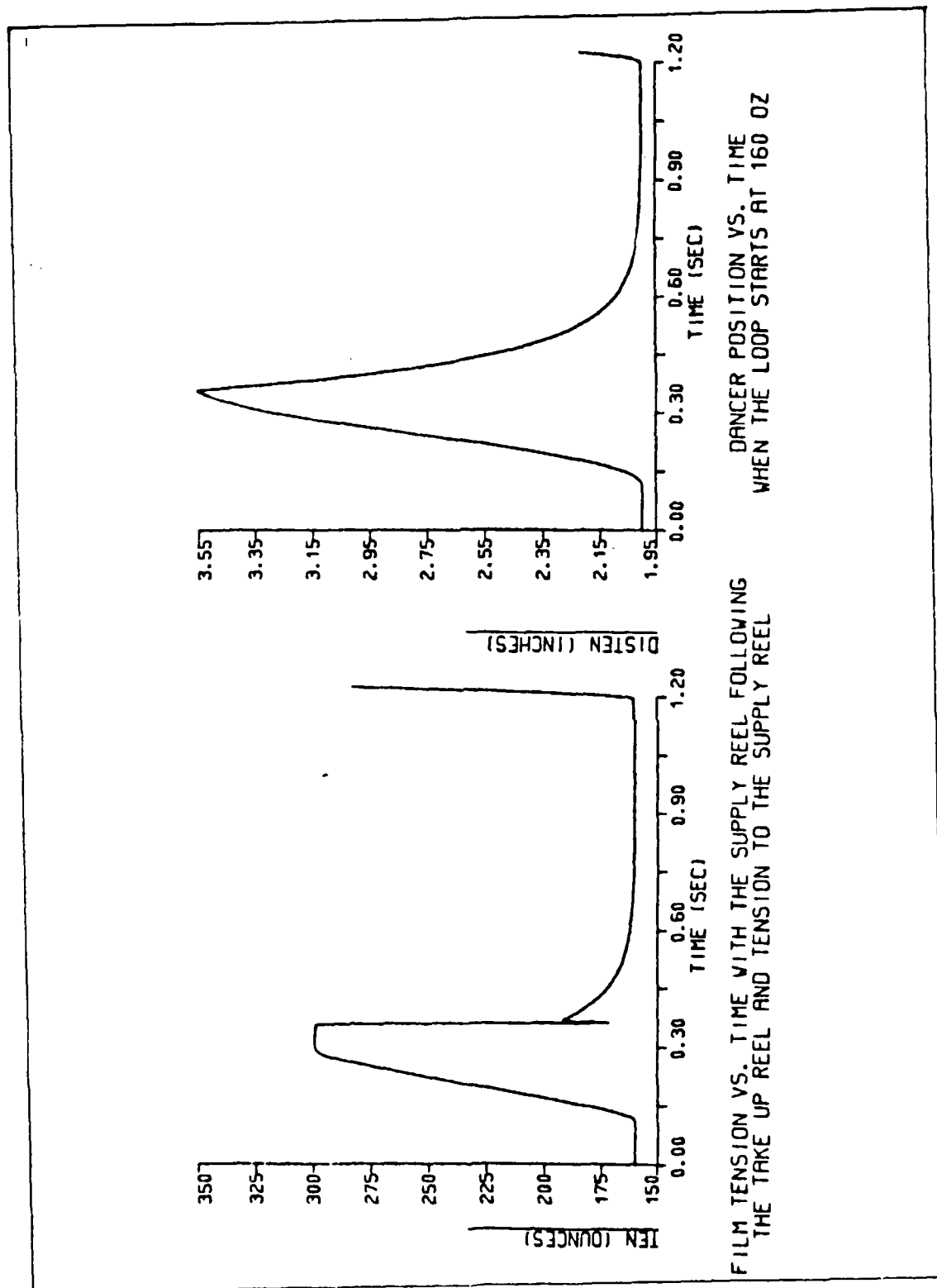
Figure 3.21   Supply Reel follows the Take Up Reel
Tension Loop in Supply Reel

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response. If the tension is too low the error signal speeds up the take up reel, which in turn acts through the last length of film to speed up the shutter. As the shutter speeds up film is removed from the first film loop which moves the dancer and increases the loop tension. This means that to correct the tension the shutter speed must be varied. This is undesirable.

For more direct control of the tension, the tension signal needs to be applied to the supply reel. This means that the take up reel will be the master and the supply reel the slave. The simulation showed a marked improvement in both tension and speed regulation. The shutter speed (Figure 3.25) is within 1 in/sec of the reference and the tension, although not constant, shows up as a small jitter around the reference value (Figure 3.26). Another thing that can be seen on Figure 3.26 is that the change in dancer displacement is only 0.6 inches as opposed to 1.2 inches when this configuration was tried initially. The speed regulation of the supply reel is not great (Figure 3.27), but the take up reel and shutter have excellent regulation and that is of greater importance.

The camera simulations now show that with an ideal tachometer speed loop, a film speed of 15,000 frames/sec can be reached and maintained. The amount of film used during acceleration is less than 70 feet which means that 330 feet to 380 feet of film are available to the photographer at 15,000 frames/sec. This shows that the idea of a 15,000 frames/sec camera is feasible, but this high speed is not always necessary. Therefore simulations at lower speeds were conducted. The speeds chosen were 10,000, 5000, and 1000 frames/sec. Because of the problems discussed earlier where film tension alone could provide enough torque to overcome BEMF and overspeed the motor, the tension for each new speed had to be different. At 10,000 frames/sec the tension of 10

60
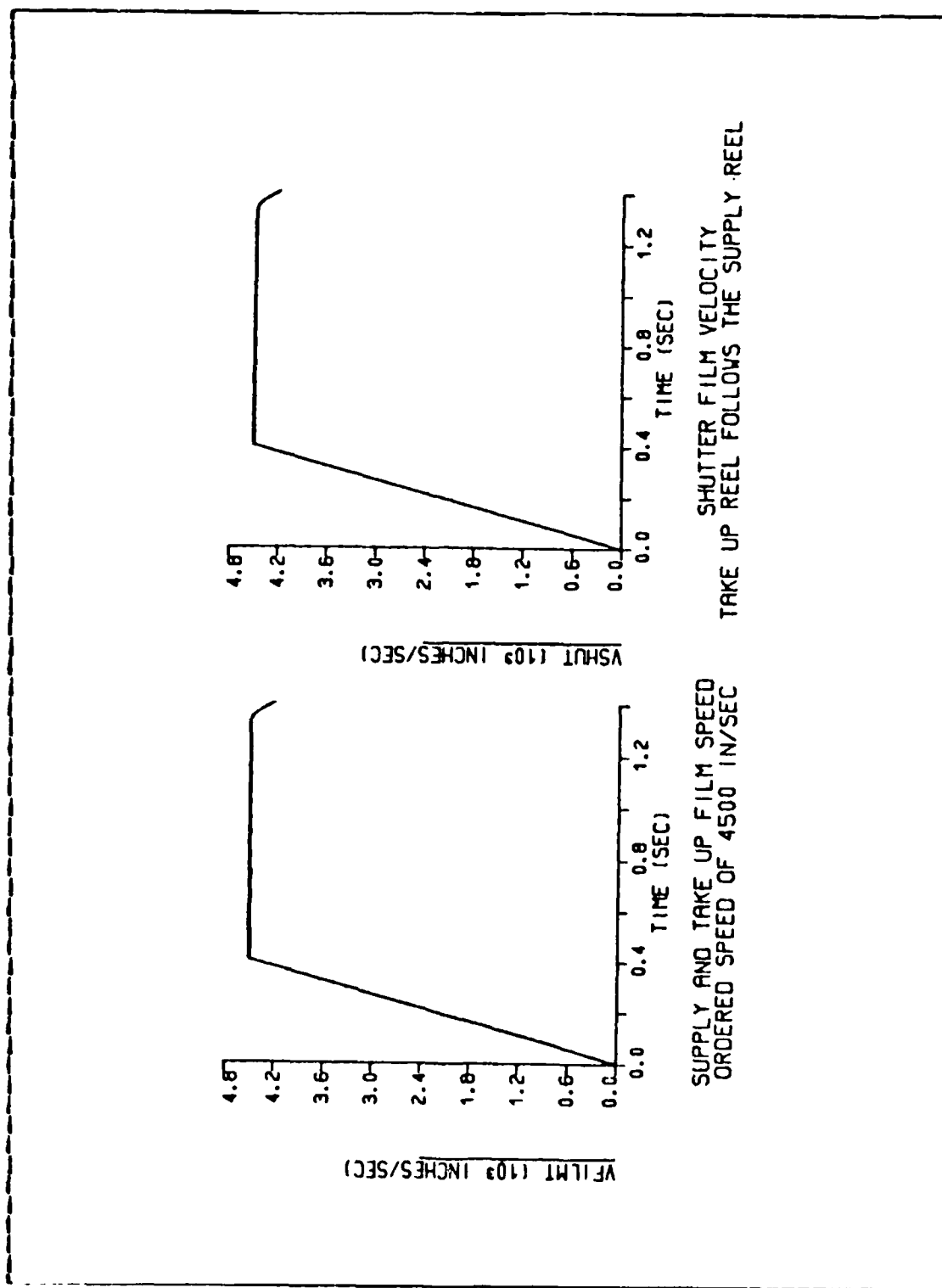
Figure 3.22 Camrea Film Velocities with the
Addition of the Shutter Assembly

61
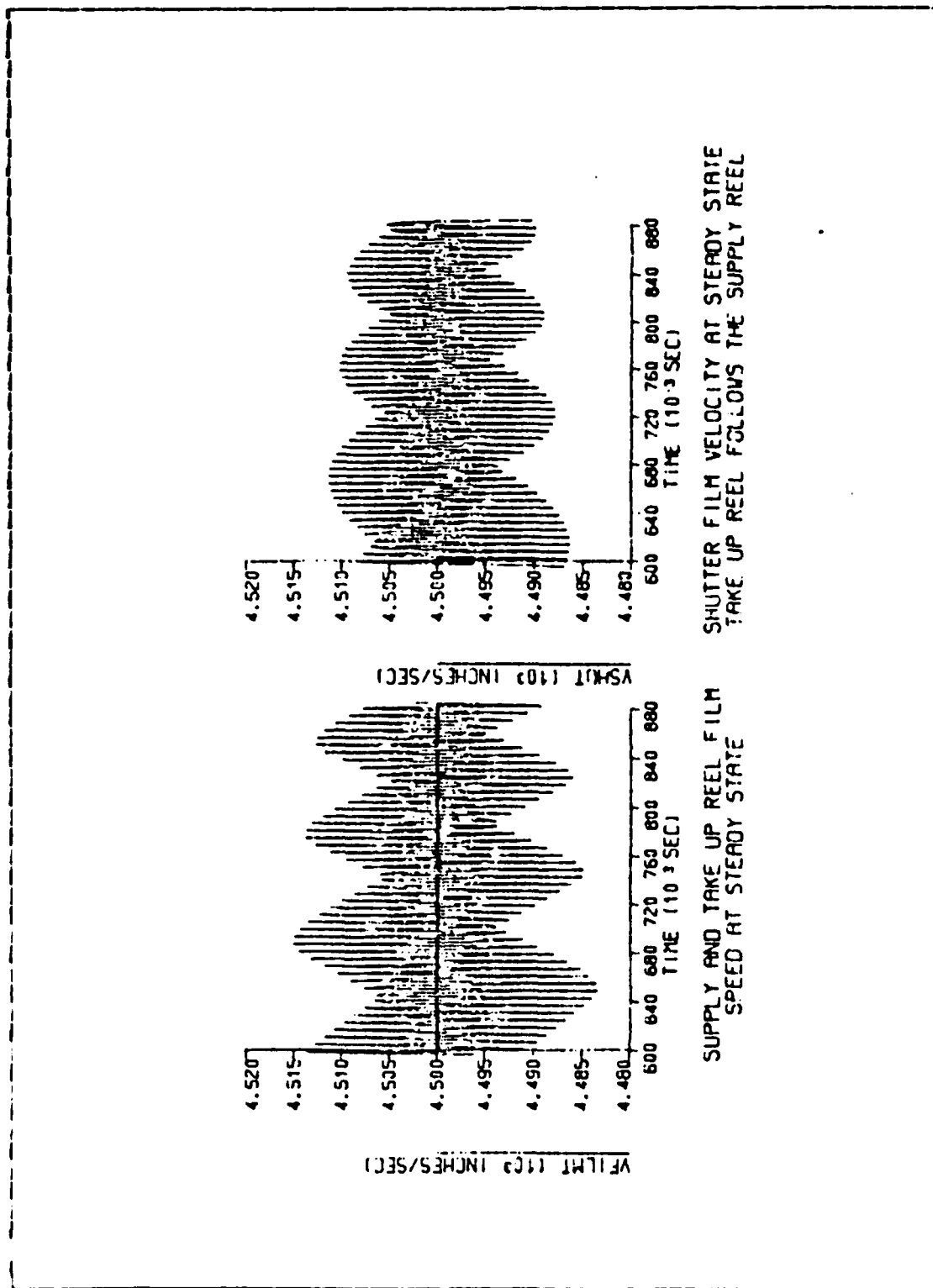
Figure 3.23   Shutter effect on Steady State Speed

62
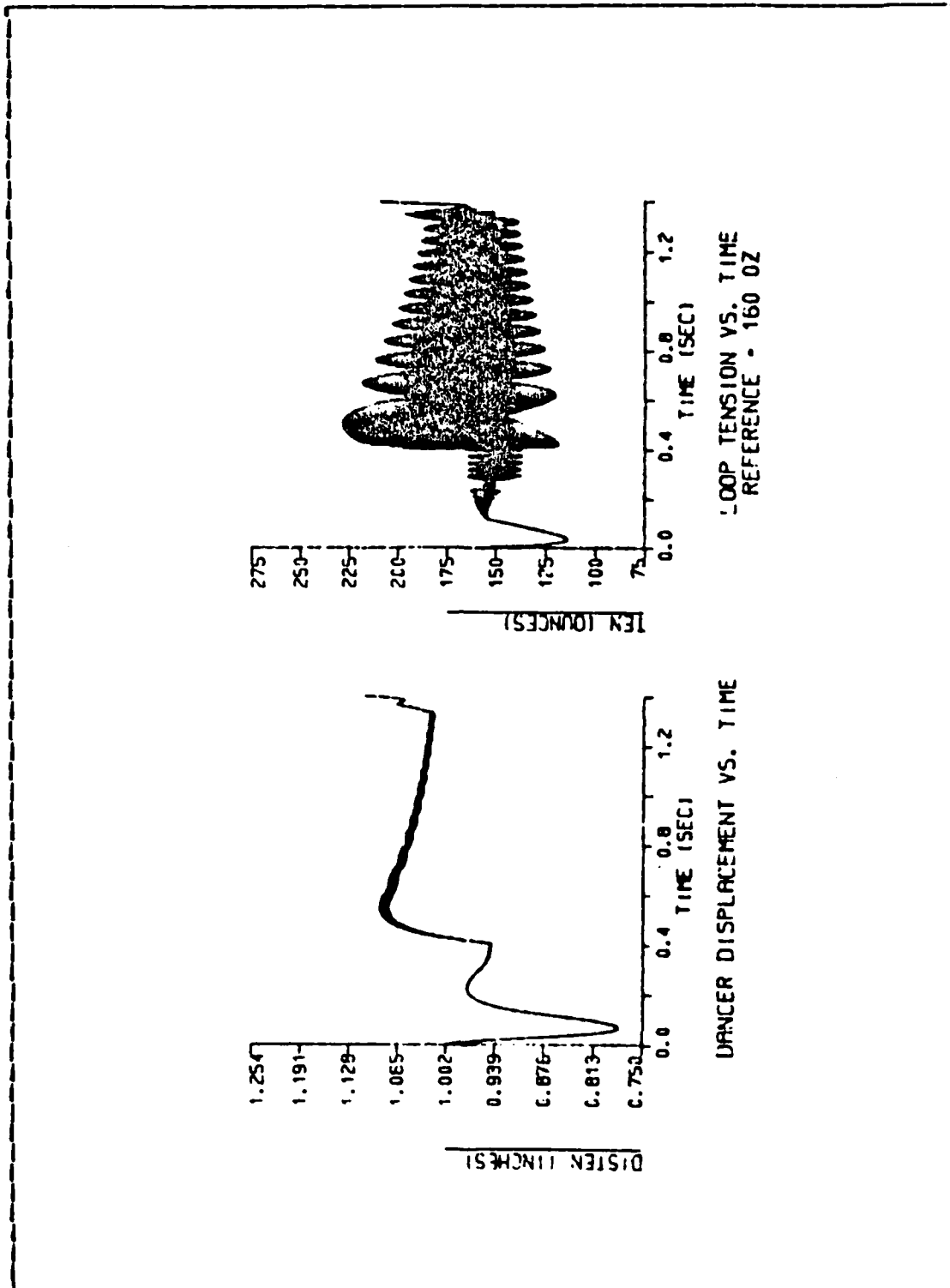
Figure 3.24   Dancer Position and Loop Tension when
Shutter Assembly is Added

63
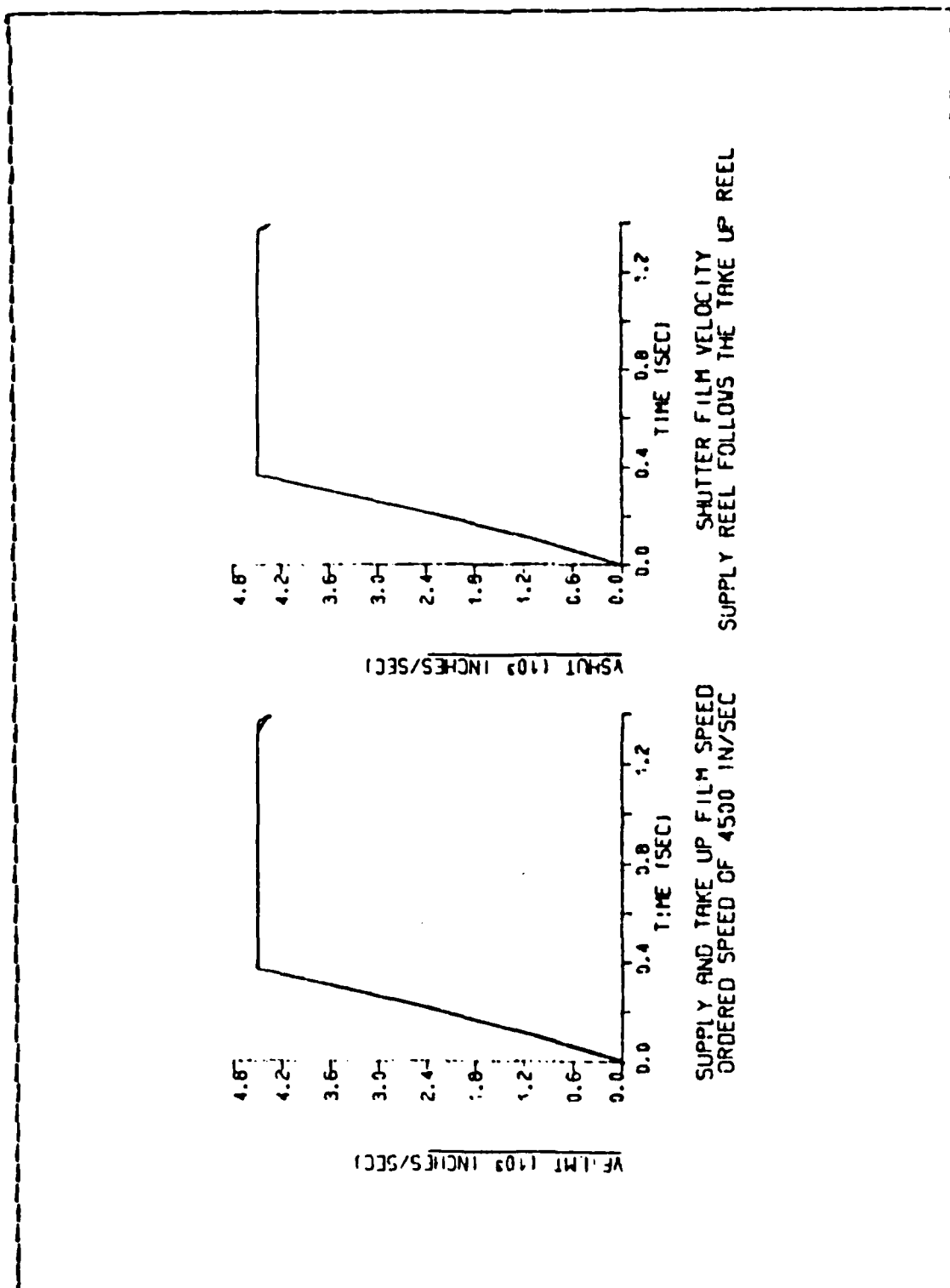
Figure 3.25   Camera with Shutter Assembly.
Supply Reel follows the Take Up Reel
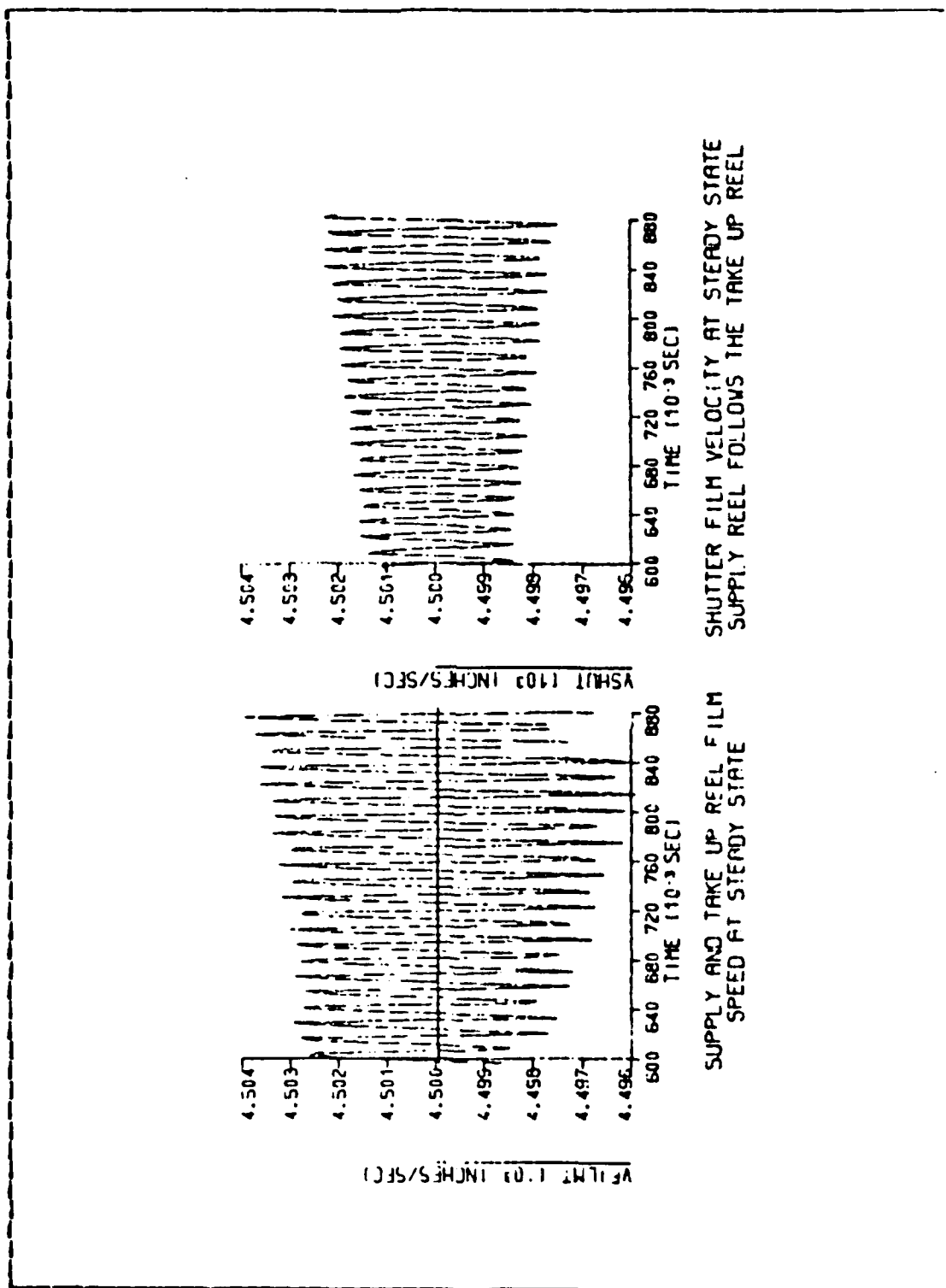
Figure 3.26   Steady State Film Speed,
Supply Reel follows the Take Up Reel

65
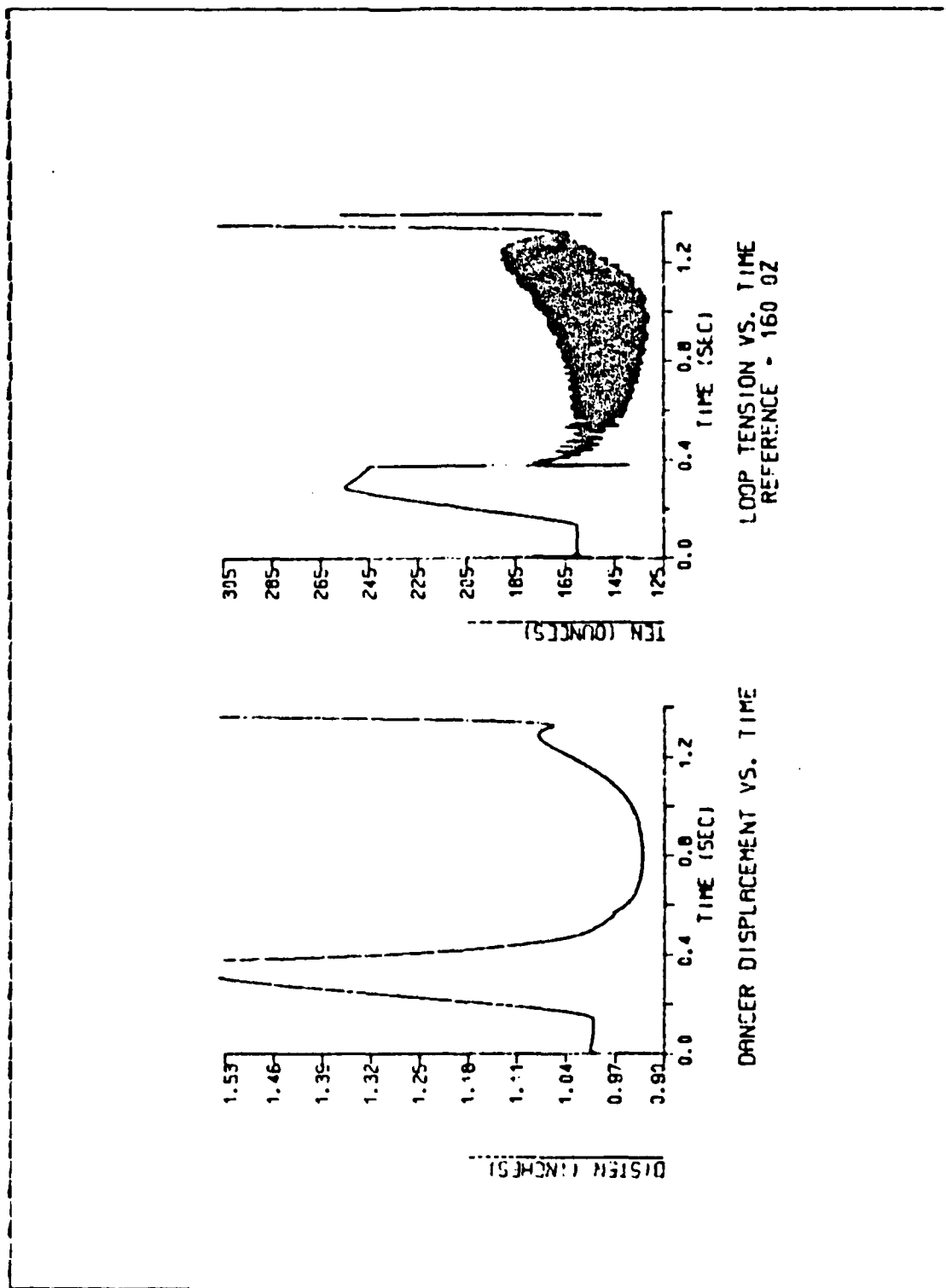
Figure 3.27   Dancer Position and Loop Tension
Camera with Supply Reel following the Take Up Reel

lbs worked fine, but 5,000 frames/sec required a tension of
2.5 lbs or less, and a maximum tension of 0.25 lbs worked
for a speed of 1,000 frames/sec. Figures 3.28 and 3.29 show
the shutter speed and tension for the simulations done for
speeds of 10,000 and 5,000 frames/sec. At 1,000 frames/sec
the results were not very good (Figure 3.30) due to the
inabililty of the loop to regulate the tension properly.
Part of the problem is the lack of acceleration time. In all
cases there is a brief fluctuation in the loop tension due
to the master-slave relationship between the two motors, but
the transient is usually taken care of during the accelera-
tion phase of the two motors. When operating at a speed of
1,000 frames/sec, the acceleration phase is so short that
the reels reach steady state in the middle of the transient.
Therefore shaping the input signal to the master to control
and slow down the acceleration time is a must. The input
command signal was changed from a step input to a ramp
input. The curve ramped from 0 to 300 in/sec in 0.2 seconds
which gave time for any transients to settle out. This idea
successfully solved the problem and good results were
achieved in simulation for 1,000 frames/sec. Figure 3.31
shows the shutter speed and the loop tension for this run.

At this point the ideal tachometer speed loop develop-
ment of the high speed camera has gone as far as it can go.
The simulations show that a film speed of 15,000 frames/sec
is realizable using two motors in a master-slave relation-
ship. It is also apparent that to get the best speed regula-
tion at the shutter the take up reel needs to be the master,
and the tension signal needs to be fed back to the supply
reel. For speeds less than 15,000 frames/sec the tension in
the loop needs to be adjusted downwards and for low speed
operations the input signal has to be shaped to slow down
the acceleration time enough to allow the tension to settle
out before steady state speed is reached.
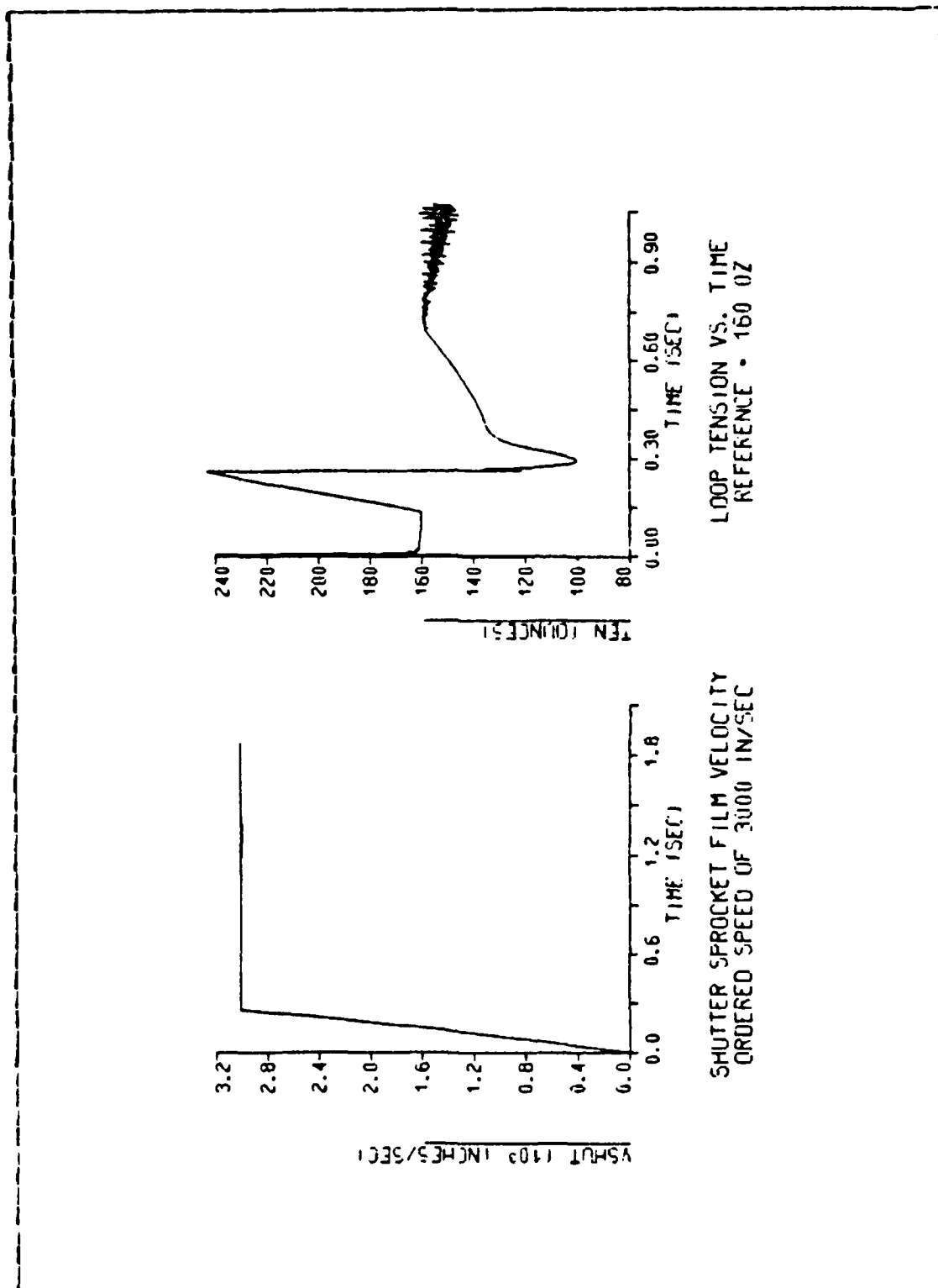
Figure 3.28   Camera Performance at 3000 in/sec

68
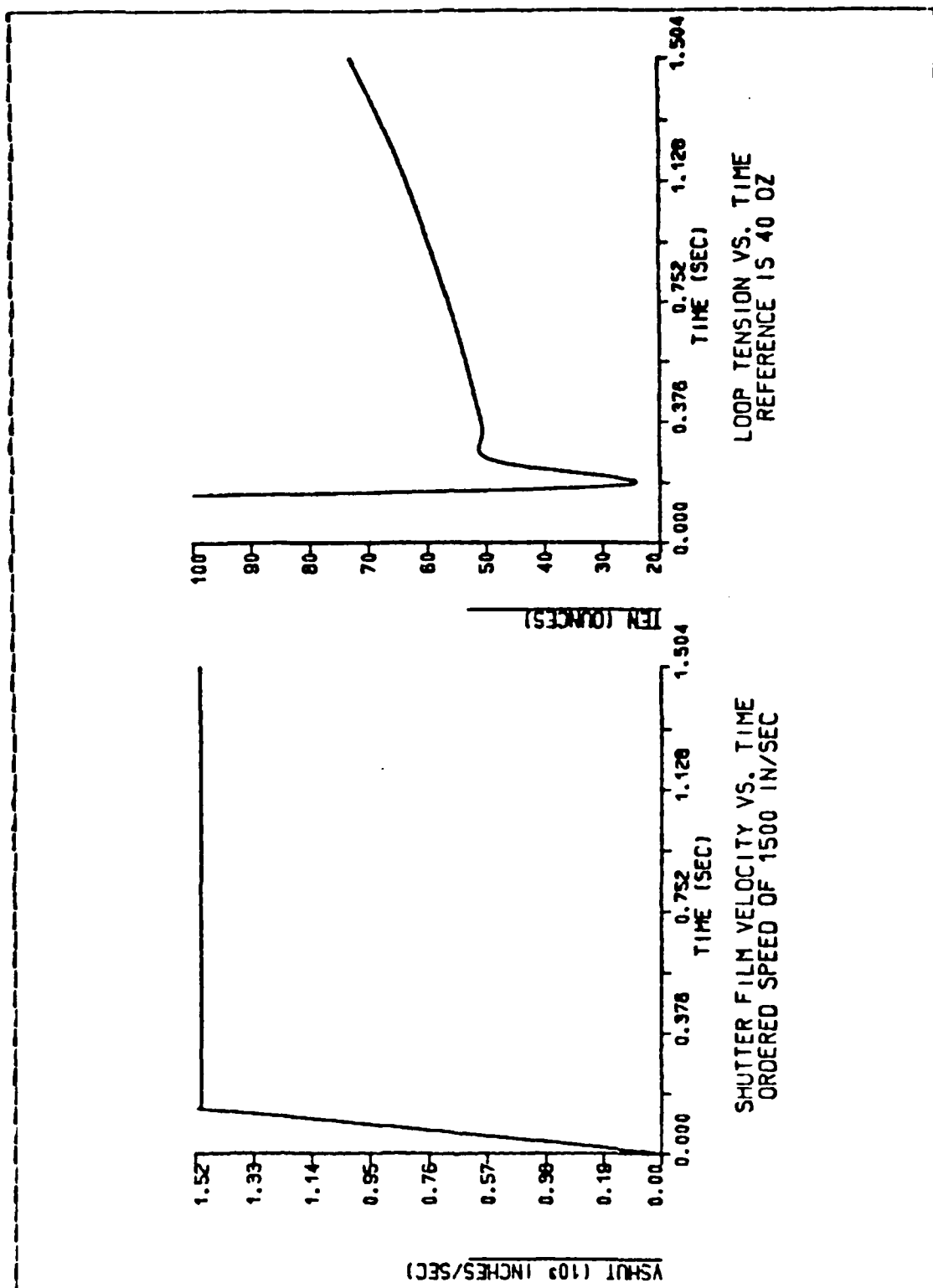
Figure 3.29   Camera Performance at 1500 in/sec
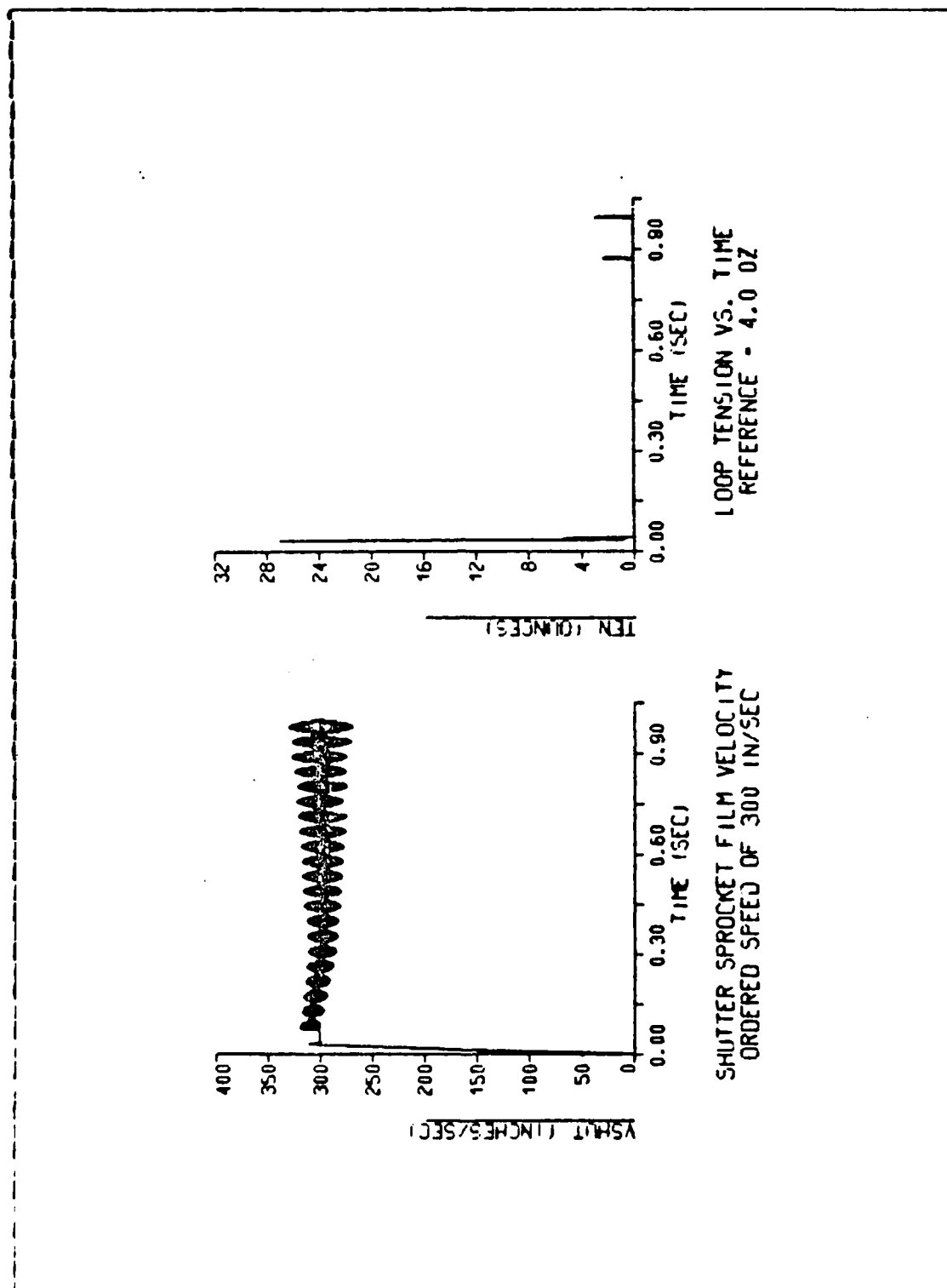
Figure 3.30   Shutter Speed for 300 in/sec
Speed Command is a Step Input

70
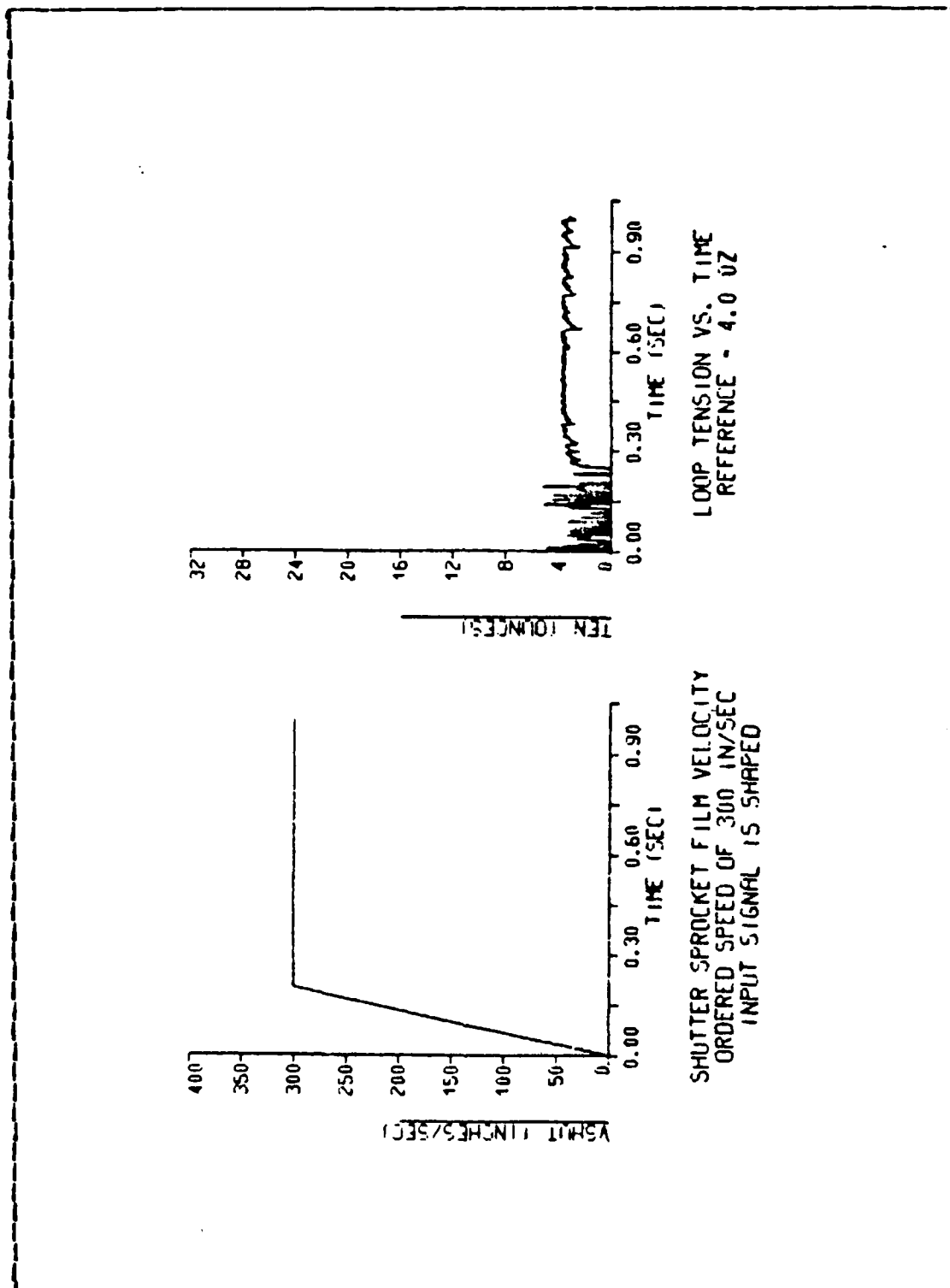
Figure 3.31   Shutter Speed for 300 in/sec
Ramp Input to the Camera

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IV. SPEED LOOP CONTROL (NON-IDEAL)

A. INTRODUCTION

In Chapters 2 and 3 simplifying assumptions were made. Simulation results were easier to obtain because of these assumptions. One of the biggest assumptions was the use of an ideal tachometer. In reality an optical tachometer or an electromechanical tachometer would have to be used, and these signals have errors in them or must be processed to obtain the frequency or velocity information from them. Another assumption dealt with pretensioning of the film. This could be a problem in that to tension the film a forward bias is placed on the take up reel and/or a reverse bias is needed for the supply reel. The last assumption is that everything stops when the film runs out. The camera actually coasts down and at these high speeds up to 50 feet of film can be destroyed in the process of coasting down. This chapter will discuss these problems as they relate to the simulation studies done so far.

B. OPTICAL TACHOMETER

The use of an optical tachometer led to two problems. The first was how to generate a pulse train in the computer that was accurate enough to use as a model in the simulations. The second was how to process the pulse train in order to get the frequency or velocity information from it.

Initially, the pulse train generation problem proved to be very difficult. The problem lay in finding a variable that provided a reliable, detectable event to be used to trigger a pulse. The first try was to use the length of the film that had moved past a fixed point. Since a frame is

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0.3 inches long, whenever multiples of 0.3 were detected a pulse would be generated (Figure 4.1). However, because of computer calculation intervals and round off errors, this method could be in error by as much as 800 Hz at steady state and this error could double during acceleration.

```
FRAME = LENG/0.3
EPS = 0.1
IFRAME = AINT(FRAME)
UPPER = IFRAME + EPS
LOWER = IFRAME - EPS
flag = 0
IF (FRAME.GT.LOWER.AND.FRAME.LT.UPPER) FLAG = 1
```

Figure 4.1   Frame Passage Detection Program

Another method was to divide the length of film by 0.3 and take the integer value of the result. At the end of each calculation interval the present value was saved for comparison to the next calculated value. At one instant in time the two values would differ. This signified the passage of a frame (Figure 4.2). This system worked very well when in

```
FRAME = LENG/0.3
FLAG = 0
IFRAME = AINT(FRAME)
IF (IFRAME.GT.PASFRAM) FLAG = 1
PASFRAM = IFRAME
```

Figure 4.2   Integer Pulse Program

steady state, but was unreliable during acceleration, which proved to be typical of most of the methods tried, including the Fortran sine function. Here the linear velocity of the

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film was converted to a corresponding frequency for one pulse per frame. The frequency was converted to radians, multiplied by time, and then the sine of this quantity was taken (Figure 4.3). This was converted into a 50% duty cycle pulse train. This method proved the most inaccurate during acceleration, and it appears as if the up ramp in frequency acts like a doppler shift so that the calculated frequency is higher than the actual frequency.

```
FRAMES = VFILMS/0.3
RADS = 2* *FRAMES
OUT = SIN(RADS)
FLAG = 0
IF (OUT.GE.0.0) FLAG = 1
```

Figure 4.3   Sine Function Pulse Program

The final solution came with installation of double precision in the DSL program. The new program also had a library routine that performed modulo arithmetic. Using this routine, the length of the film modulo 0.3 was generated. This routine combined with double precision arithmetic gave a pulse train that was accurate. The program and its output are shown in Figures 4.4 and 4.5 . These pulses can now be used to generate velocity signals for control of the camera motors.

Initially the idea was to count pulses over a fixed interval of time. This count could then be converted to a voltage, or could be used as the entry to a table where the error signal would be read out directly. To get accurate results the system must have good resolution. For example, counting a 15,000 Hz pulse train for one millisecond would result in 15 counts. If the count is off by one the answer

would be either 16,000 or 14,000 Hz which means that the resolution is 1 KHz. This is not very good. To improve the resolution two things can be done. The time interval can be

```
FRAME = AMOD(LENG,0.3)
FLAG = 0
IF (FRAME.GE.0.15) FLAG = 1
```

Figure 4.4   Pulse Program

increased and/or the pulse rate can be increased. In this case, the time to accelerate to steady state speed is 0.4 seconds. In order to maintain control the time interval needs to be small. At one millisecond there would be 400 samples during the acceleration phase. Therefore the number of pulses per frame or the frequency of the pulse train needs to be increased. Looking at the resolution, at least 100 pulses per frame are needed. This means that over one millisecond 150U counts would be normal and an error of one count would be an error of 10 Hz. This seems a little sloppy, especially when compared to the ideal speed loop results, but could be acceptable. This would also mean that the optical disk would have to have about 7,000 lines, and the detector would have to be able to respond to a signal of 1.5 MHz. Both of these are within the realm of modern technology. All this looks good, but in the computer it means that the sample time is so small that the program will not run within the accounting time constraints, and therefore for computer simulation studies this idea was not used. In reality this seems simple and could give results and therefore is probably worth looking into.
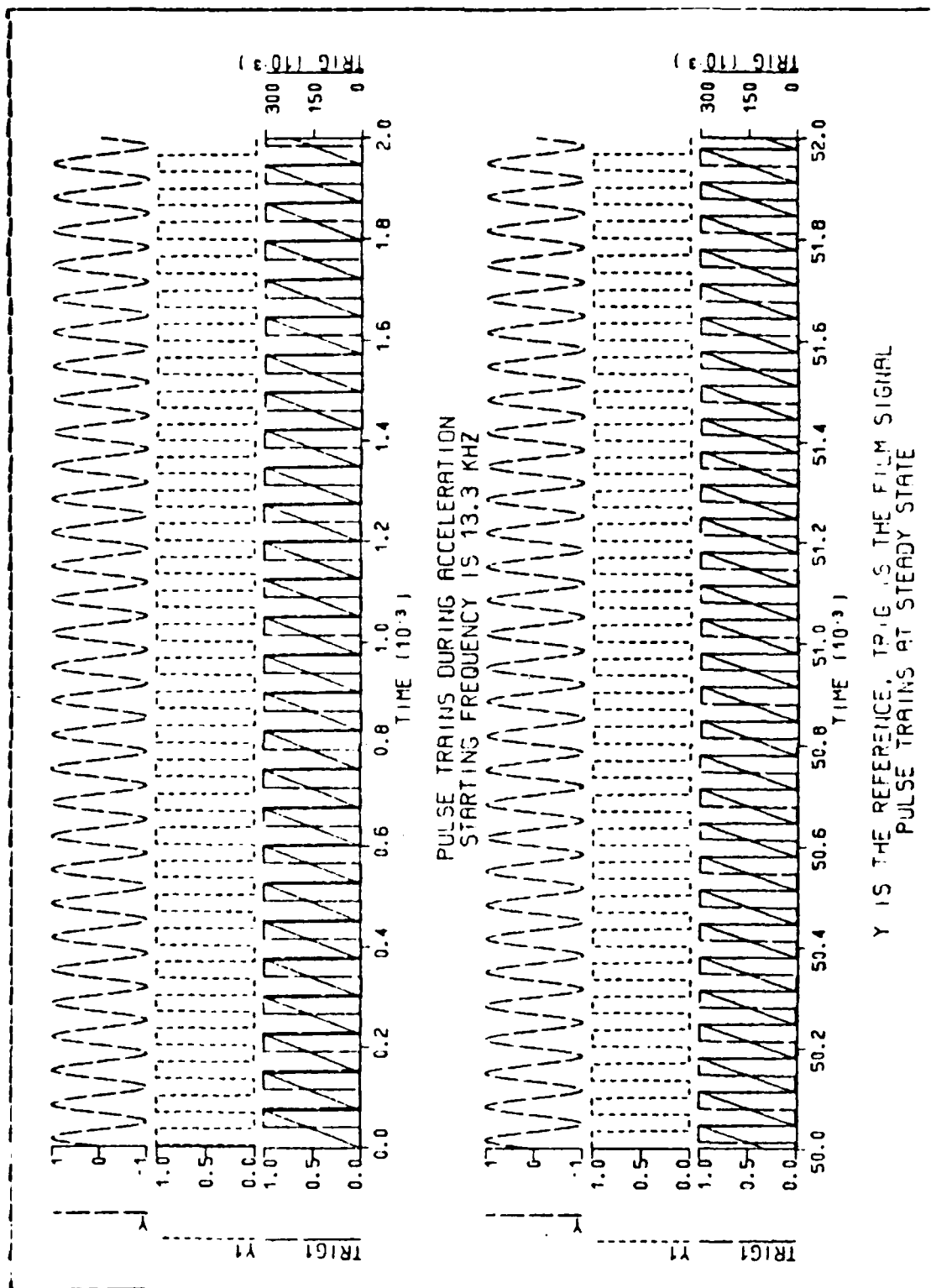
Figure 4.5   Pulse Program Output

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The next idea was to send the pulse train through a low pass filter and use the DC value of the pulse train to control the motor speed. Using a pulse train with a fixed pulse width the DC value would increase as the frequency of the pulses increases. This DC level would be compared to a reference to generate the error signal. The problem with this approach is that the motor and filter response must be well matched. If the filter bandwidth is low enough to provide a smooth DC signal, then it is not fast enough to provide a signal that accurately represents film speed. In this case, when the film has reached the desired speed the filter output is still generating an output that indicates the film is below speed. Therefore the system overshoots and begins to oscillate. If the bandwidth of the filter is increased then the amount of ripple in the film signal becomes a problem.

Because straight low pass filtering of the pulse train did not work, lead-lag networks were examined to see if the results would improve. The Bode diagram of the system indicated that either a lead network or a lag network would work. Initially a lead network was designed, but the vertical wave fronts coming into the differentiator caused problems, and the results were very poor. Therefore a lag network was used, but here the problem of the mismatch between the system and the filter response occurred again. Since low pass filtering and lead-lag networks did not work another method of error signal generation was needed.

The final idea involved comparison for the integral of signal and reference pulse trains. The signal and reference pulse trains are integrated over one period of the reference signal. The values for these two signals are compared and saved and the integraters are reset. This method was first tried on the supply reel alone and the width of the pulses was set at 80% of the steady state period. Using this the

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output showed fairly wide fluctuation and there was a steady
state error of five inches/second (Figure 4.6). After
careful consideration it was found that the fluctuations
were largely due to the pulse width. If the situation occurs
where the two pulses are exactly aligned the film signal can
gradually fade , but the error signal will not pick it up
until the error is gross. To overcome these problems the
reference frequency was increased and the pulse width was
increased to 99% of the reference period. The results while
not spectacular (Figure 4.7) were good enough to incorporate
this system into the full camera simulation program. The
results here improved over the supply reel simulations. The
shutter speed (Figure 4.8) was not as smooth as hoped for,
but the variation was no more than 15 frames/sec at steady
state. This is only 0.1% of the desired value. Figures 4.9
and 4.10 show the shutter film speed and the film tension
for a complete run using optical tachometer feedback. The
results show that this is a viable method of control for the
camera.

C. PRETENSIONING

In the previous discussions and simulations of the
camera it was assumed that the film was already at the
desired tension when the run started. As a practical matter
this would not be true and if the film were slack when the
filming was started, the sudden jerk when the slack was
removed could snap the film. To avoid this problem, when the
camera is turned on the film must be put under tension. To
accomplish this three things can be done: the take up reel
can be driven forward while the supply reel is held, the
supply reel can be driven backward while the take up reel is
held, or the reels can move in opposite directions until the
desired tension is reached. In each case there are advan-
tages and disadvantages which will be discussed.

78
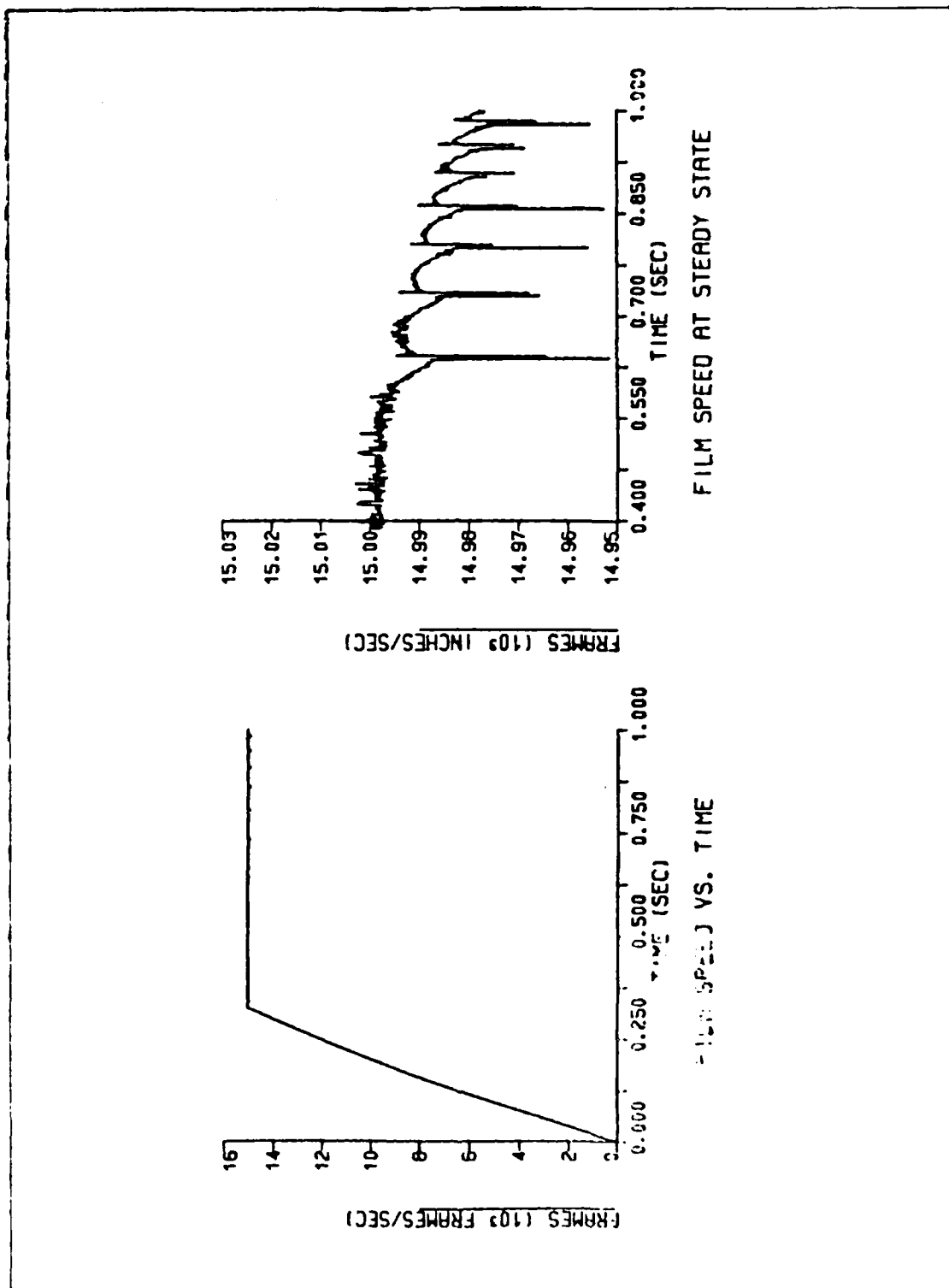
Figure 4.6   Optical Tachometer on Supply Reel.
Pulse Width is 80% Duty Cycle
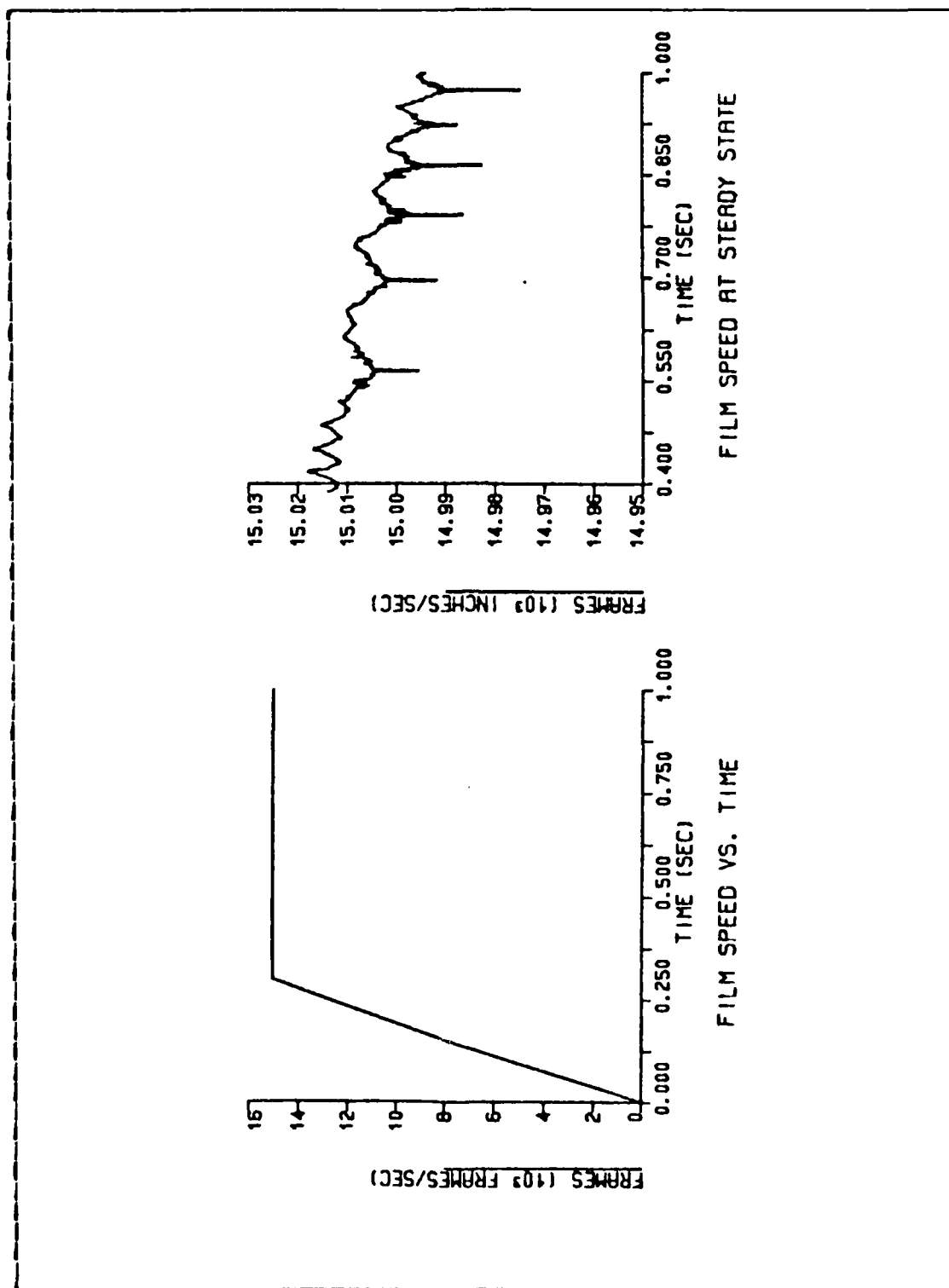
Figure 4.7   Opitcal Tachometer on Supply Reel.
Pulse Width is 99% Duty Cycle

80
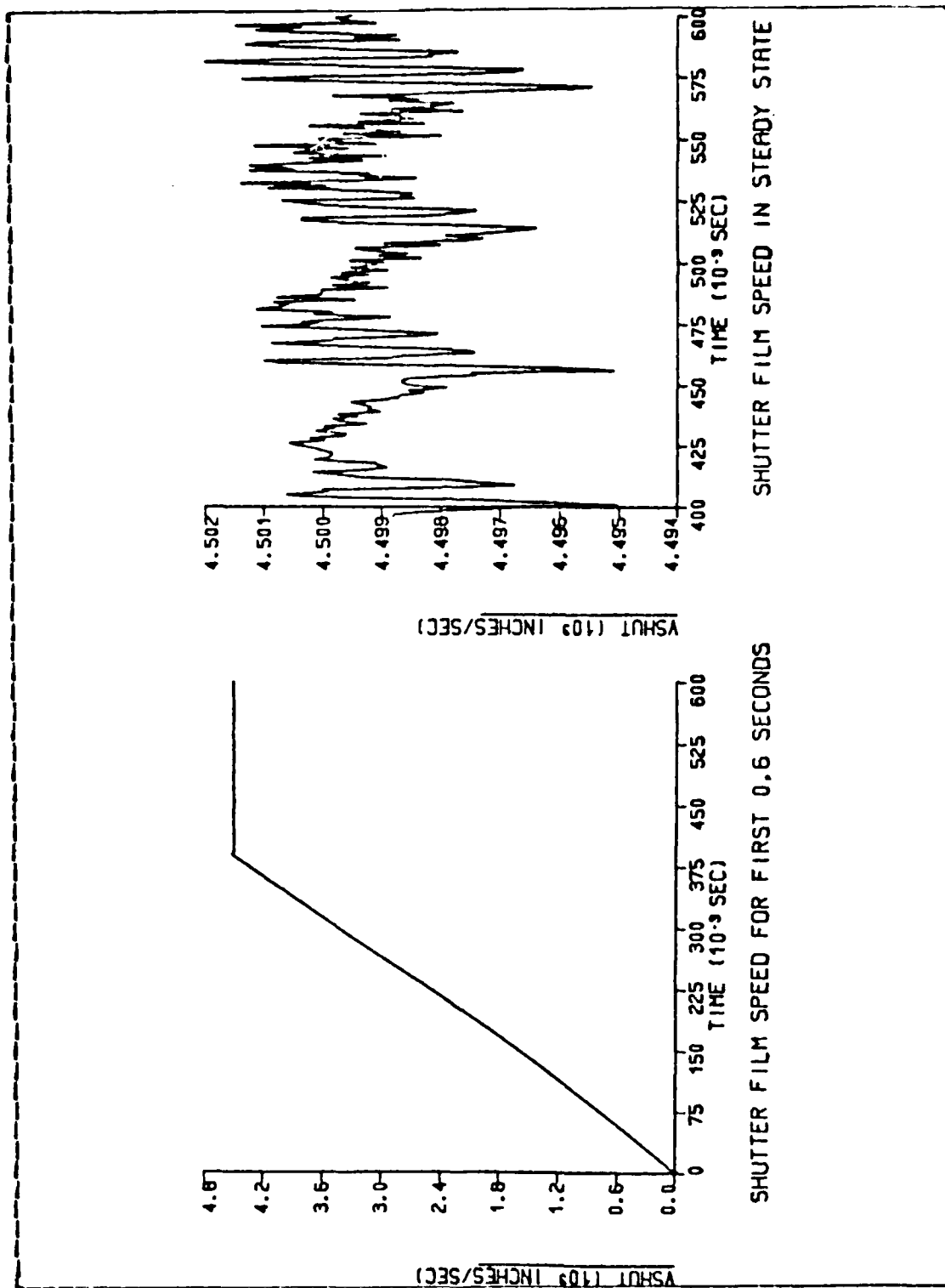
Figure 4.8   Shutter Film Speed using the Optical Tachometer

81
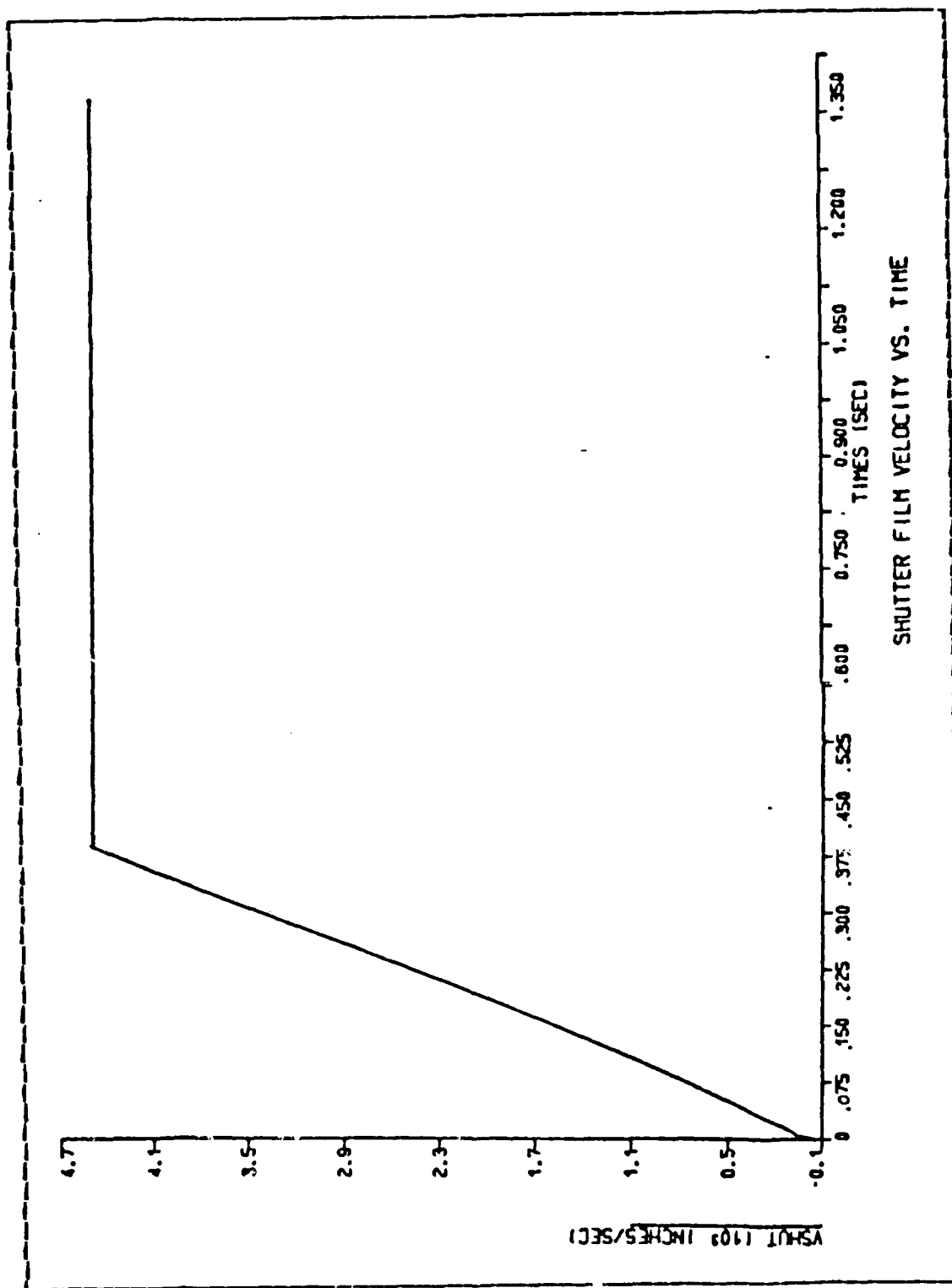
Figure 4.9   Shutter film velocity for a full run using
the optical tachometer signals for speed control

82
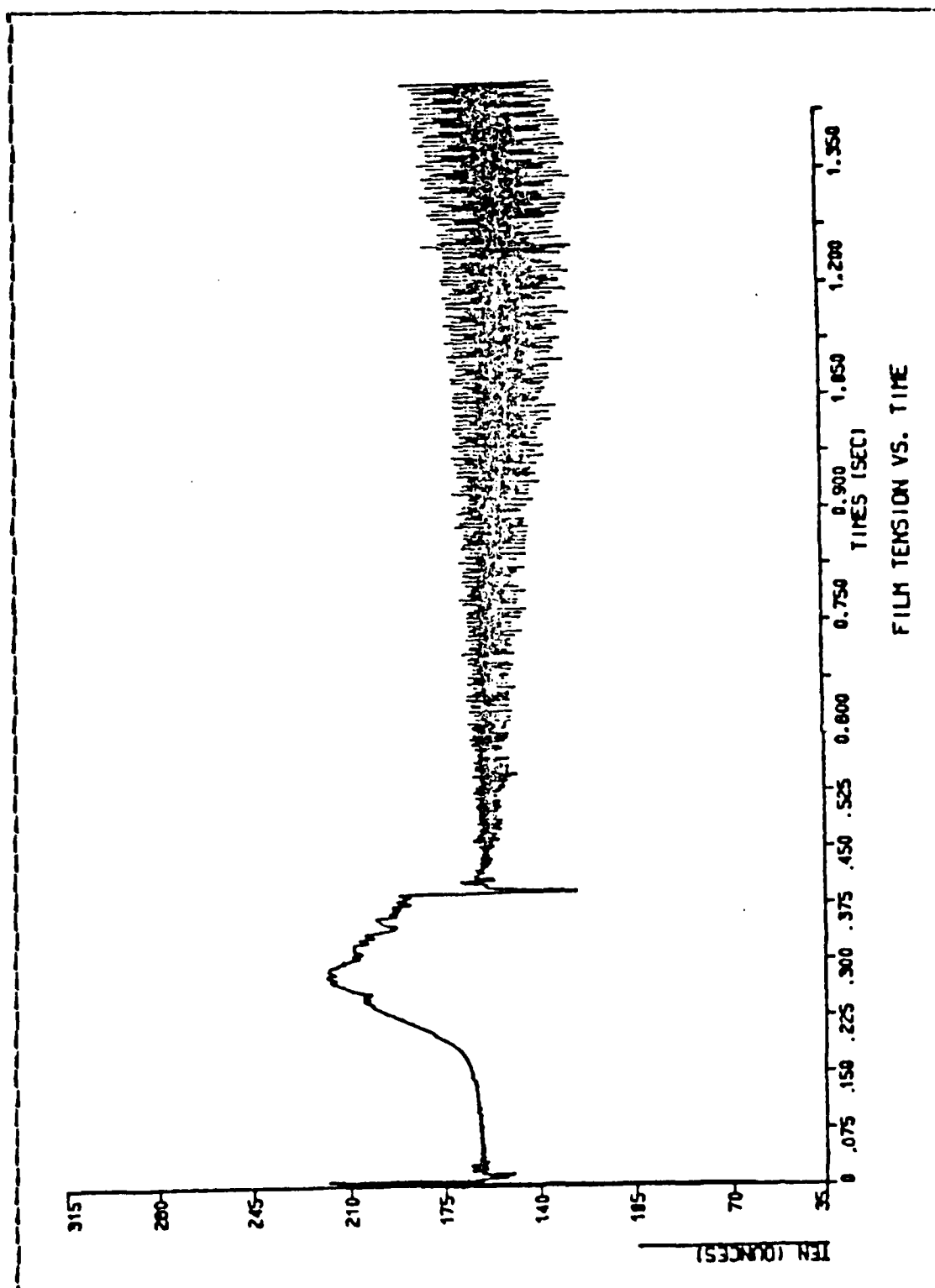
Figure 4.10   Film Tension for the Full Run

The initial scheme applied the tension error signal to
the take up reel while the supply reel was held with a
brake. This has the advantage that the take up reel is
already moving in the direction that it will go once filming
commences. The drawback is that normally the tension signal
is fed only to the supply reel. Therefore logic and
switching must be used to feed the tension signal to the
take up reel during tensioning. The results of this scheme,
shown in Figure 4.11, indicate that this is a viable
scheme.

The second approach tried was to use a small dual power
supply for tensioning of the film. This has potential advan-
tage of not switching the error signals, but it does require
switching of the power supply to the motors. Another advan-
tage is that the smaller power supply will draw less power
while maintaining the film tension. The great disadvantage
is the extra hardware involved in the additional power
supply. One other consideration is that full tension can not
be maintained by a small, +10 volt, power supply. Therefore
to make this work the tension reference signal must be
lowered during tensioning. Here the results are good except
that the two reels move forward very slowly. If the camera
was to be used soon after it was turned on this is not a
problem, but if the camera were set up and tensioned a few
hours prior to the filming the problem could be prohibitive.
Figure 4.12 shows the results when the film is tensioned for
0.2 seconds prior to the filming.

The last method of tensioning the film is to put a brake
on the take up reel and drive the supply reel backward until
the film is at the proper tension. The advantage here is
that the existing power supply and signals are used. The
disadvantage is to make the supply reel move backward a
negative power supply is needed. One way to accomplish this
is to switch the existing power supply connections, however

84
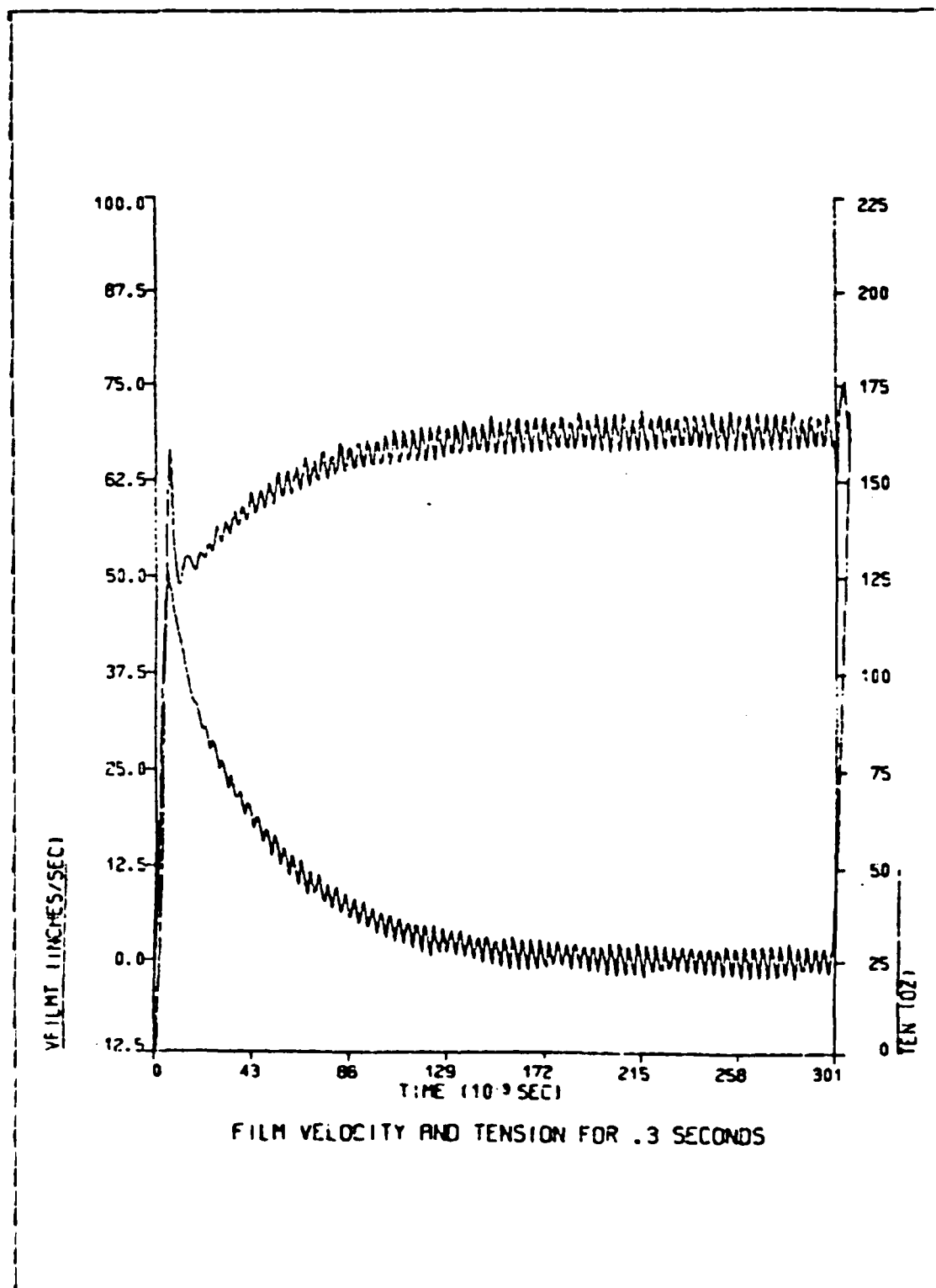
Figure 4.11   Take Up Reel Tensioning
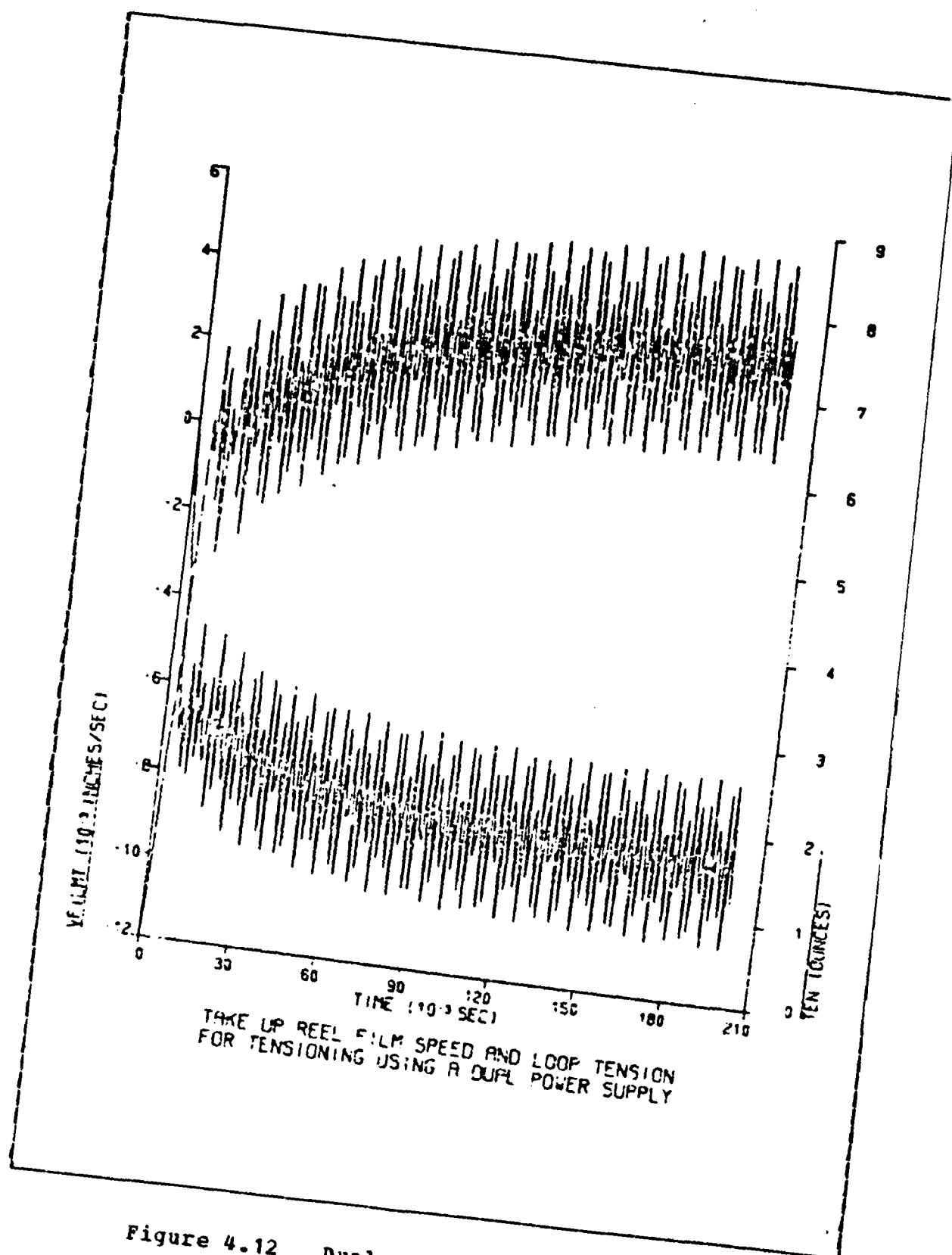
Figure 4.12   Dual Power Supply Tensioning

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the error signals must also be switched. Again, as in the case where the supply reel was braked the results (Figure 4.13) were quite good.

The preceding results indicate that a brake, even though it means extra hardware, is needed to keep the reels from moving during the tensioning of the film. Since a brake is needed, either the first method or the last method would be preferred. Each method involves switching and therefore there is little to choose between them.

D. DECELERATION

As stated at the beginning of this chapter, if the film is not slowed down prior to the end, the last 50 feet will tear and break as the take up reel slows down. To prevent this the system must be slowed down to less than 7000 frames/sec prior to the end of the film. This way even though the speed of the film is not right the qualitative information contained on the film is not destroyed.

From the previous discussion of the tensioning of the film it was seen that two methods were feasible. Each of these methods dictates a different deceleration method. If the brake is put on the take up reel then only a positive power supply is available, which means that the supply and take up reels can only be driven in the forward direction. Therefore the motors can only coast down using dynamic braking. Because of the large inertias involved the time for this is excessive (0.65 seconds) and it would require about 250 feet of film. This is too much, especially when compared to the goal of 50 feet. Also it takes 80 feet of the film to reach steady state which only leaves 120 feet out of a 450 ft reel of film to take pictures at the design speed. Therefore this method is not very useful.
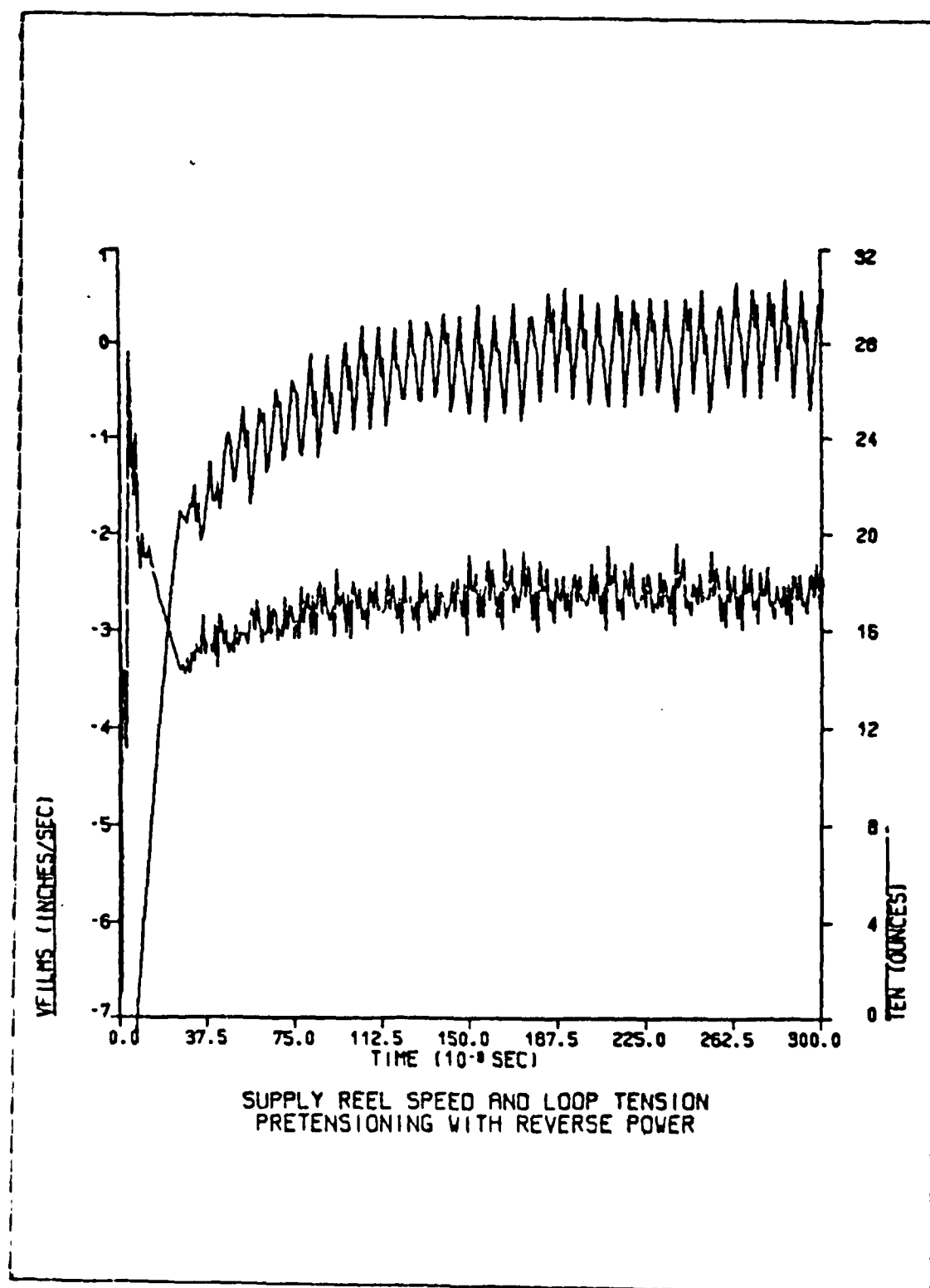
Figure 4.13   Supply Reel Tensioning

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The last tensioning method also works well for deceleration. In this case the power supply is reversed to both motors and this provides power to slow the system down. Using this system the film can be slowed down from 15,000 to 7,000 frames/sec (4500 to 2100 in/sec) in just 0.2 seconds (Figure 4.14). During this time only 700 inches or 58.3 feet of film are used. This scheme was also tested for a run at 300 inches/sec where the film was tensioned, ramped up to 300 in/sec, held, ramped down to 0 in/sec, and then kept under tension. The results, shown in Figure 4.15, were excellent.

The last two figures, Figures 4.16 and 4.17, show the shutter film velocity and film tension for a complete run using the optical tachometer. The film is first tensioned for 0.1 seconds to a value of 16 ounces. The low value was chosen because the system uses less power to maintain a low value than a high value. Then a step of 4500 in/sec is used to start the run. The camera then runs at steady state until there are only 58 feet of film left. At this point the take up reel and supply are decelerated until the film runs out which terminates the run. The results again show that this system can get to steady state and maintain steady state speed.
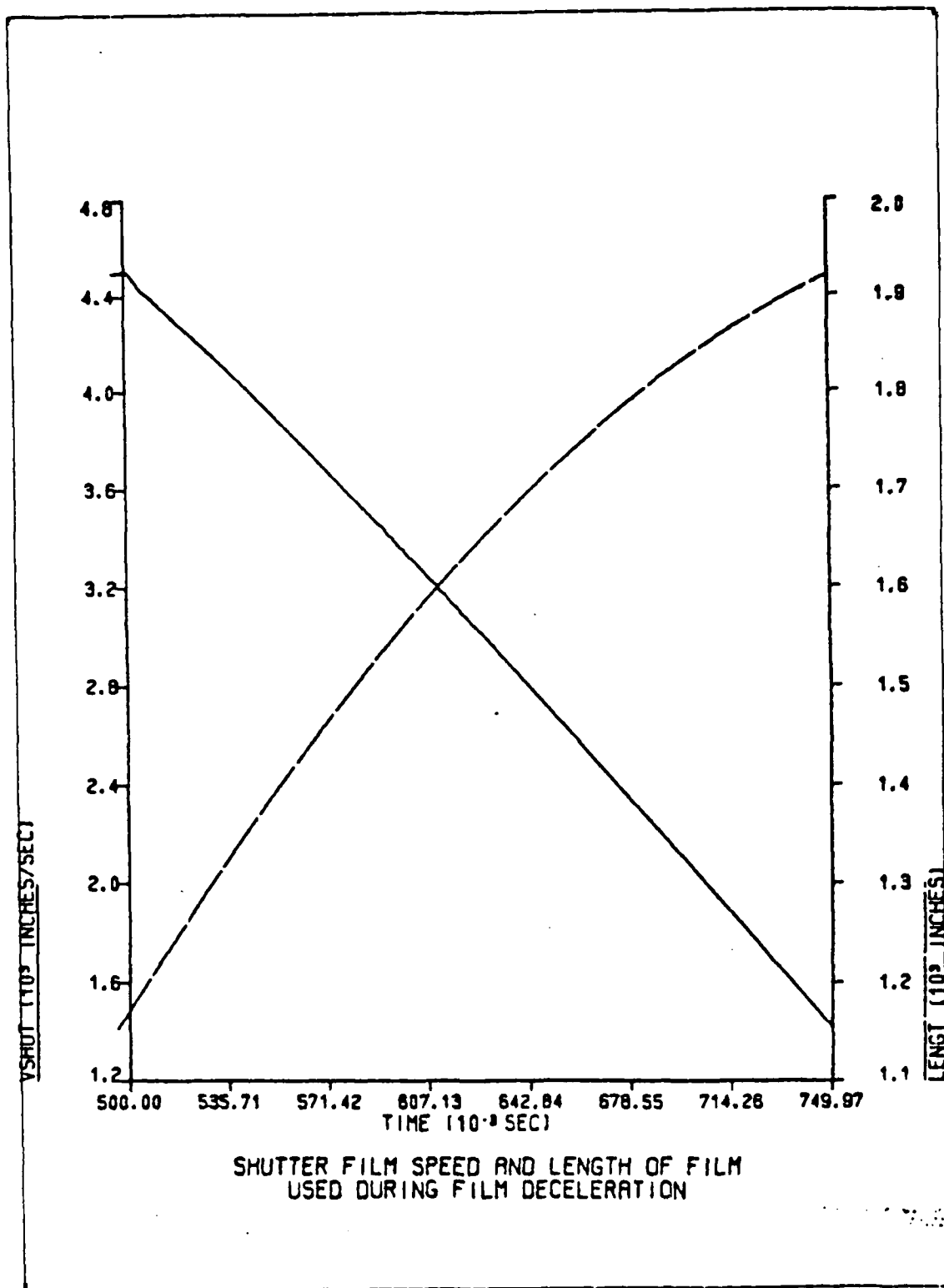
Figure 4.14   Deceleration Using Reverse Power
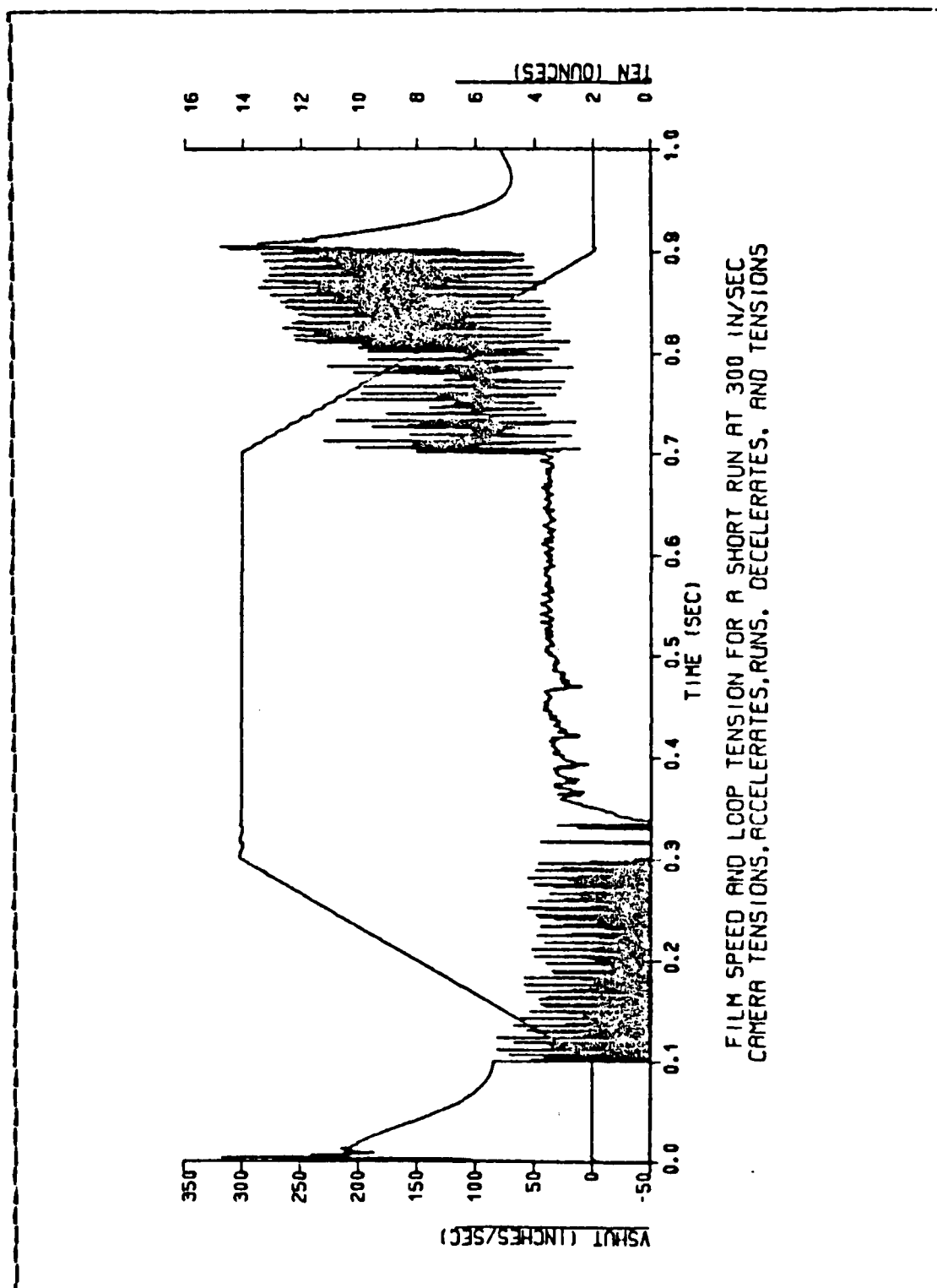
90

Figure 4.15   Short Low Speed Run

91
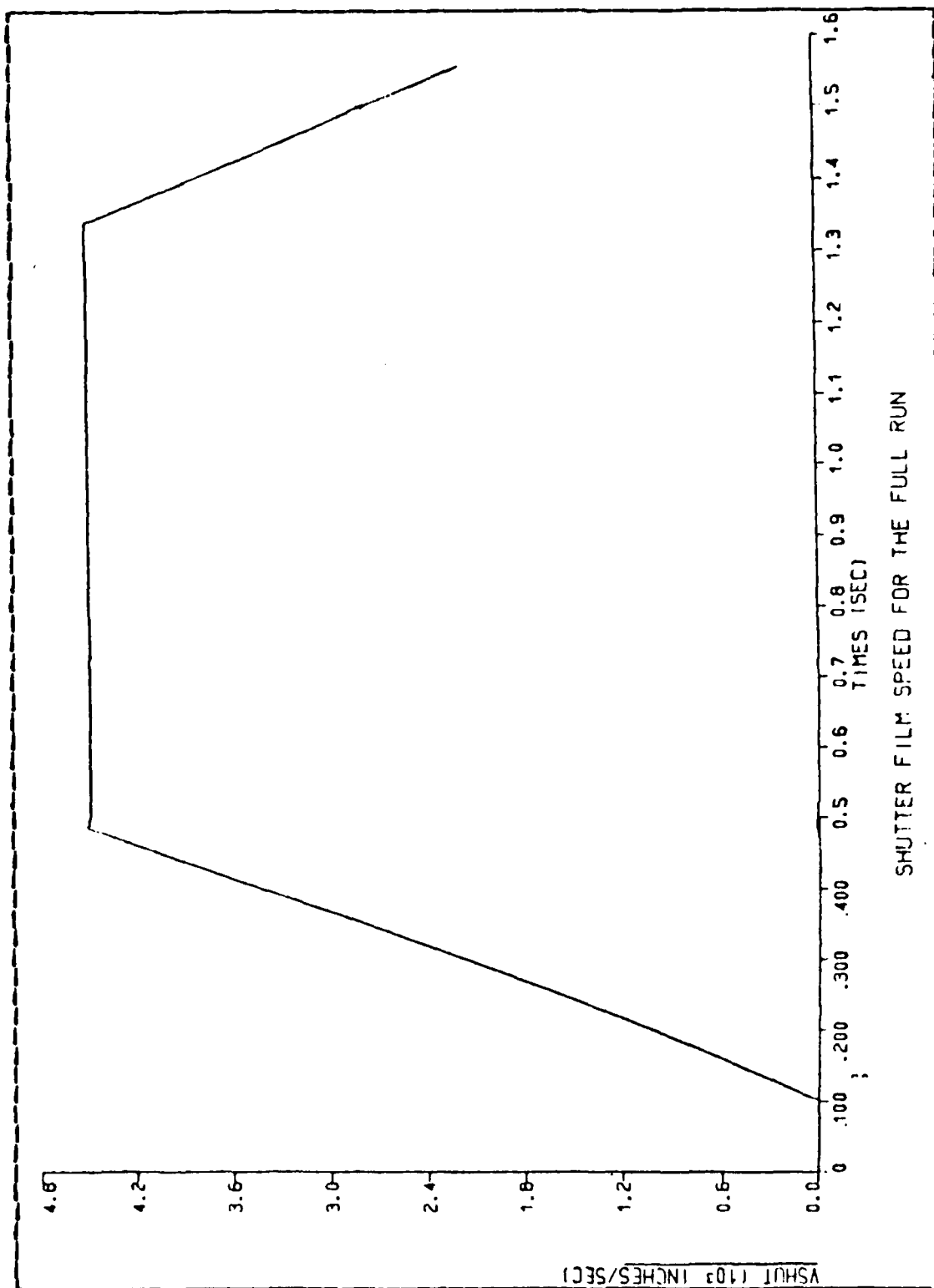
Figure 4.16   Shutter Film Velocity for the Full Run

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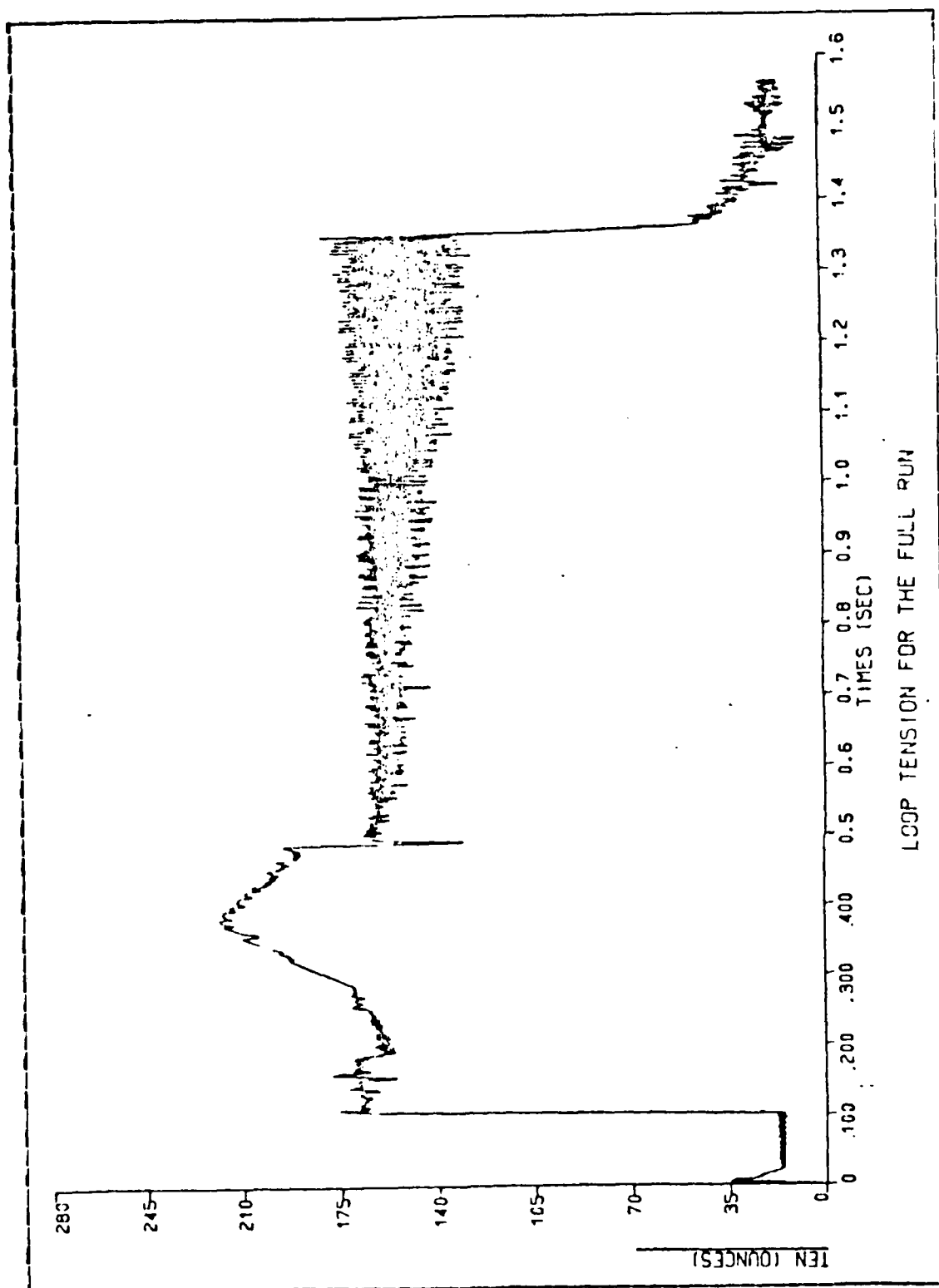
Figure 4.17   Film Tension for the Full Run

V. PHASE LOCKED LOOP CONTROL

A. INTRODUCTION

The preceding chapter discussed speed control using the optical tachometer, and the problem of steady state error. The phase locked loop has become an increasingly popular method of overcoming this problem. There are two reasons for this: the first is that the phase locked loop has zero steady state speed error and the second reason is that the optical tachometer is a better velocity transducer than the electromechanical tachometer. However the phase locked loop does not normally provide for variable speed operation. If a change in torque load or speed occurs the loop can break lock and may not be able to re-lock.

The way to overcome these difficiencies is to use a dual mode controller. A velocity error signal is used to accelerate the motor to synchronous speed. Once the motor is up to speed the phase error locks in the system and eliminates steady state error. Figure 5.1 shows a block diagram of the system. [Ref. 4]

B. VELOCITY ERROR

The velocity error is generated with the optical tachometer as discussed in Chapter 4. However other circuits have been used to obtain the velocity error signal. One such circuit is shown in Figure 5.2 . In this circuit the output is a DC representation of the frequency or velocity difference between the two input pulse trains. Another method uses a phase locked loop to measure the frequency content of an input pulse train. Again the output is a DC signal that is proportional to the input pulse train frequency. These are
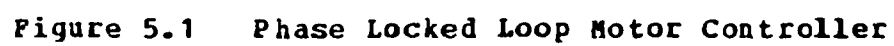
94

Figure 5.1   Phase Locked Loop Motor Controller

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END

FILMED

DTIC

1.0	4.5 5.0 5.6 6.3 7.1	2.8	2.5
		3.2	2.2
		3.6	
1.1		4.0	2.0
			1.8
1.25		1.4	1.6
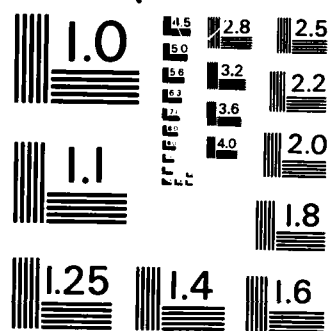
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

two of many circuits that are available to convert a
frequency signal to a voltage signal. However it is very
hard to model these circuits and still retain the real
uncertainty present such as noise and other electronic inac-
curacies. Therefore the same technique, integrate and hold,
developed in Chapter 4 is used here to get the velocity
information from the input pulse train.
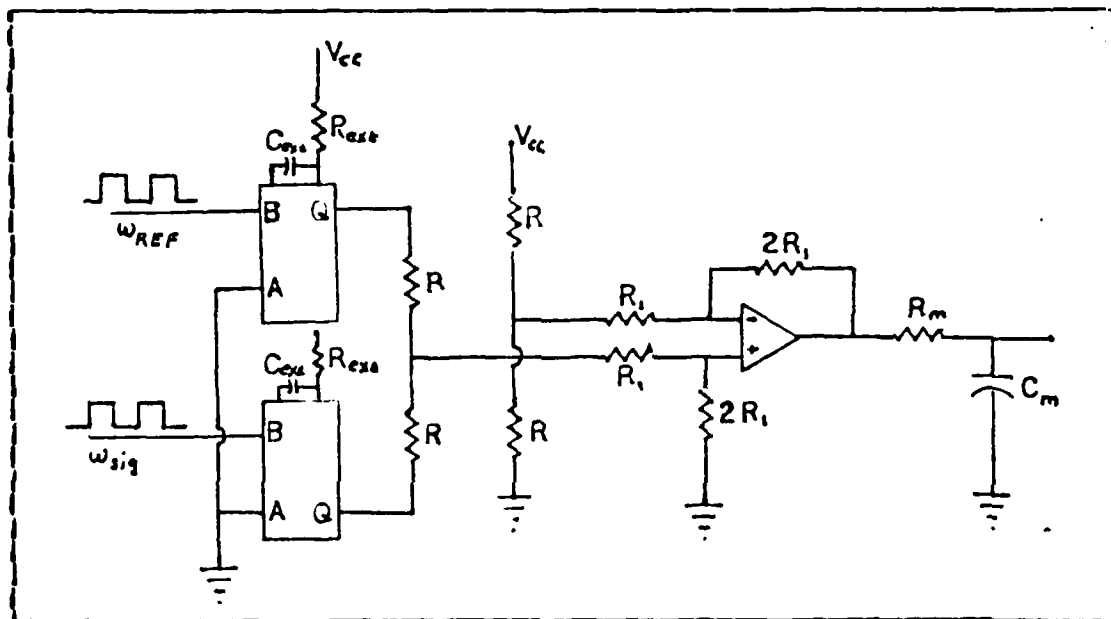
Figure 5.2   Velocity Error Circuit

C.   PHASE ERROR

In speed control applications of the phase locked loop
the difference in phase between the reference pulse train
and the motor pulse train is a position error and is not
important as long as it remains constant. If the phase error
is constant then the loop is frequency locked.

Figure 5.1   Phase Locked Loop Motor Controller

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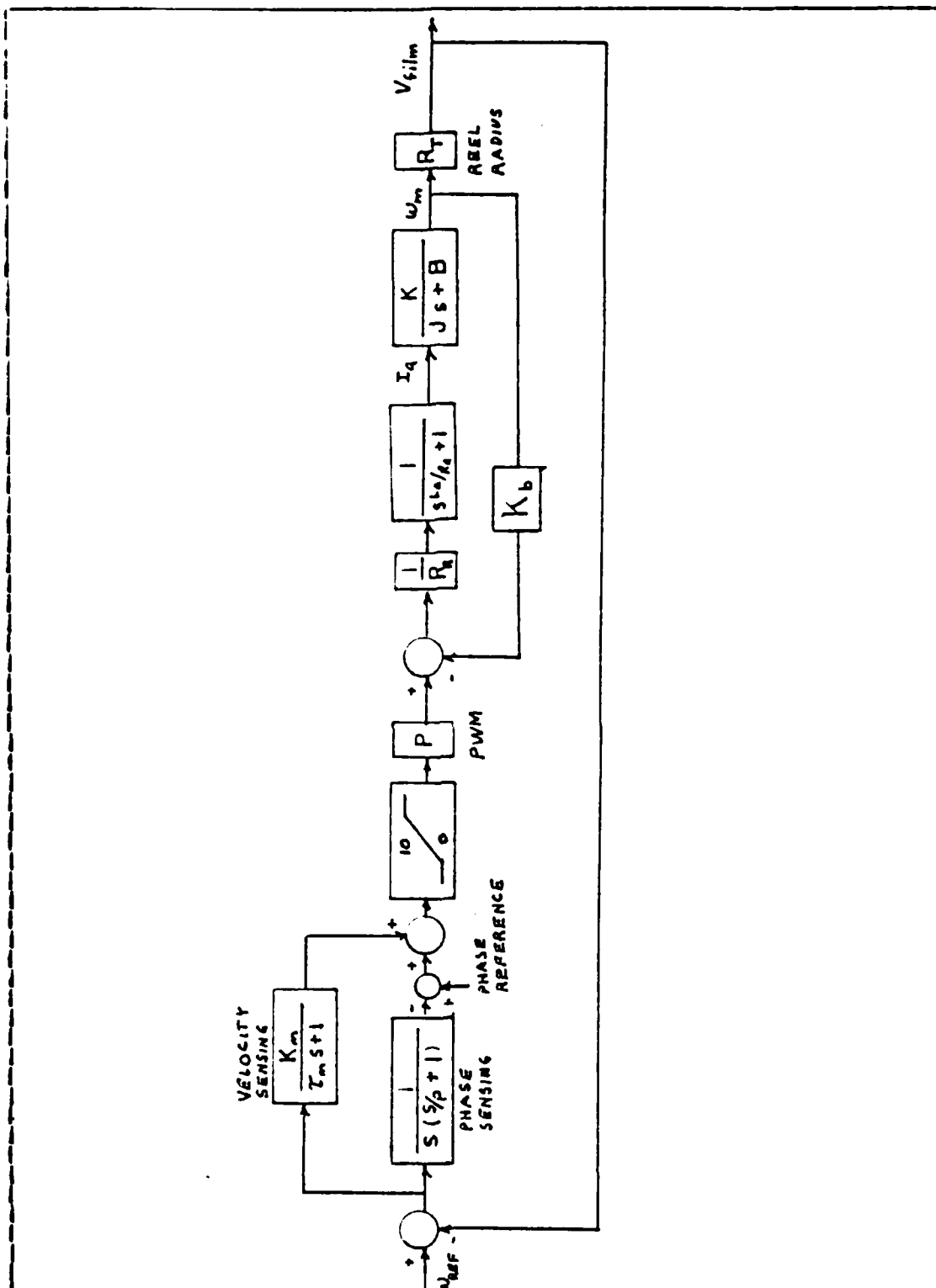
The phase error signal is generated from the output of a two state counter. Two pulse trains, reference and signal, are applied to the counter. The leading edge of the signal pulse counts the counter up and the leading edge of a reference pulse counts down. Since the output is either high or low, the pulse width of the output is a measure of the phase difference between the two pulse trains.

The first attempt at phase locked loop control did not use a dual mode controller. In this single mode system the phase error signal generated by the two state counter described above was used to control the power switch directly. Therefore the pulse width of the power to the motor is the same as the pulse width of the phase error signal. At start up the pulse width is almost 100% and the system accelerates up to the desired speed. Due to negative feedback the position error (pulse width) decreases as the motor approaches steady state speed, but unless the steady state phase error required to maintain ordered speed is met exactly as the motor reaches steady state speed, the motor will overshoot in speed. The amount of phase difference needed to maintain a steady state of 4500 in/sec is only about seven degrees, and an error greater than this accelerates the motor. When the motor overshoots the ordered speed the phase error pulse width decreases until a phase difference of seven degrees is reached, and then the motor begins to decelerate. Since the motor speed is still greater than the reference speed, the phase error pulse width continues to decrease until it reaches zero. At this point, due to the nature of the two state counter, the pulse width jumps to 100% and the motor starts to accelerate. This is a condition known as cycle skipping and it is an unstable condition. Attempts to stabilize the loop were not successful.

A successful solution was found by averaging the phase error pulse train with a low pass filter and comparing the

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resulting DC signal with a chosen DC reference level. Since the phase error signal is a "square wave" of 10 volts amplitude, the range of the DC average is from 0 to 10 volts as the phase difference ranges from 0 to 360 degrees. If a reference level of 5 volts (180 degrees) is chosen, the DC error signal will vary from -5 volts to +5 volts. With this reference level the system reference and output pulse trains will try to lock at 180 degrees out of phase when the ordered speed is reached.

The above DC phase error signal is combined with the velocity error signal to form a dual mode controller. The velocity error provides the necessary signal to accelerate the motor up to the desired speed. As the system approaches steady state speed, if the phase difference is not 180 degrees, the system will either slow down or overshoot the ordered speed. In doing so the phase relationship between the reference and output pulse trains is adjusted so that as steady state is reached the system locks. As stated earlier, this requires a constant phase error signal at steady state, and therefore at steady state the expected phase difference between the system reference and output pulse trains is about 187 degrees. When referenced to 180 degrees this will produce a net positive error of 7 degrees which is enough to maintain an ordered speed of 4500 in/sec.

The phase locked loop speed control was first tried on the take up reel alone. The results were as good as the results obtained when using the ideal tachometer feedback in Chapter 3. Figure 5.3 shows the film speed in frames/sec at the take up reel for the whole run and a close up of the film speed from 0.35 to 0.351 seconds. The reference and film pulse trains are shown in Figure 5.4 and here it looks as if the phase match is exact. In reality there is about a 7 degree phase difference between the two pulse trains. The data from the simulation run shows a deviation of +2 frames

98
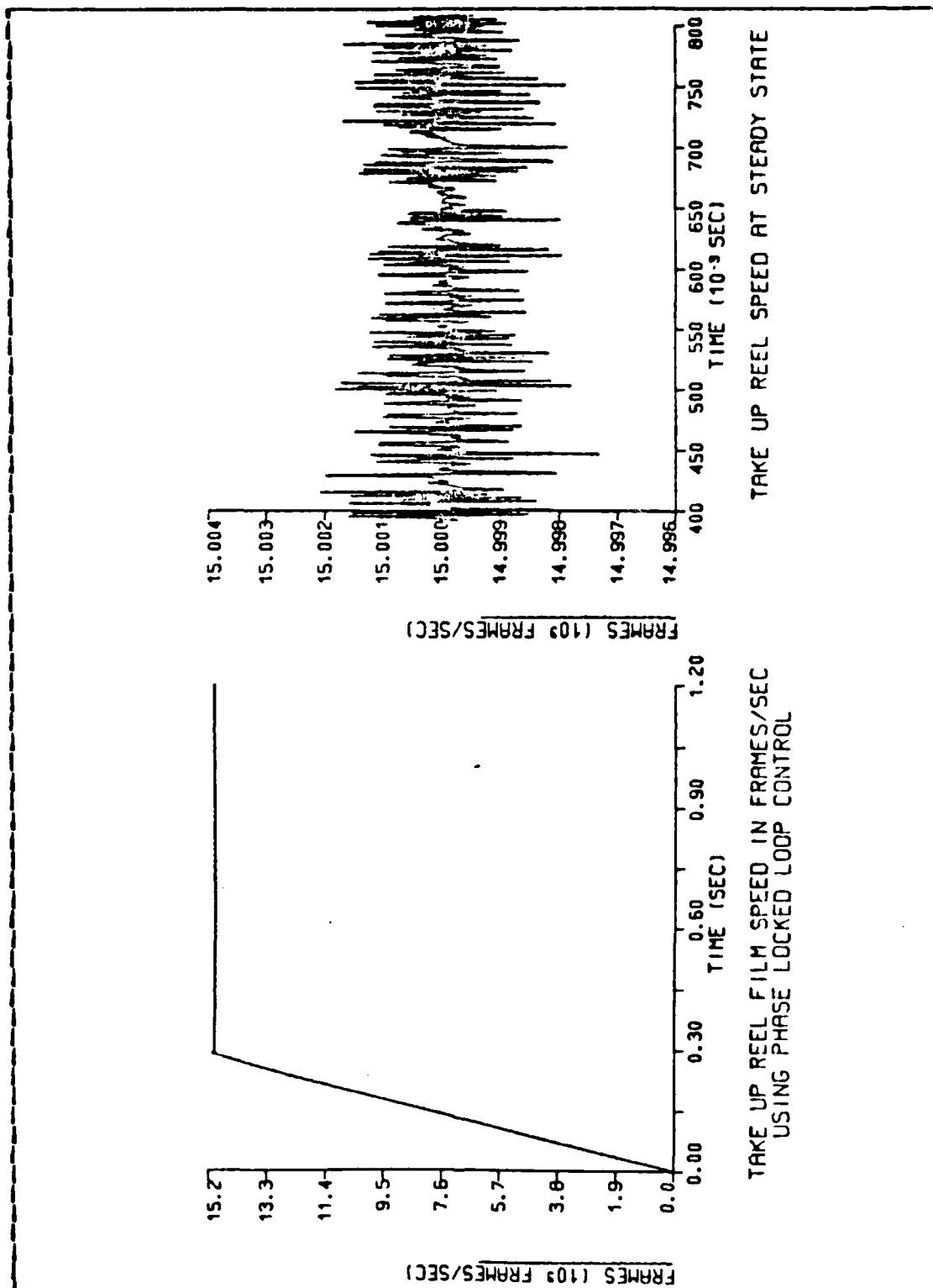
Figure 5.3   Take Up Reel Film Speed with PLL Control
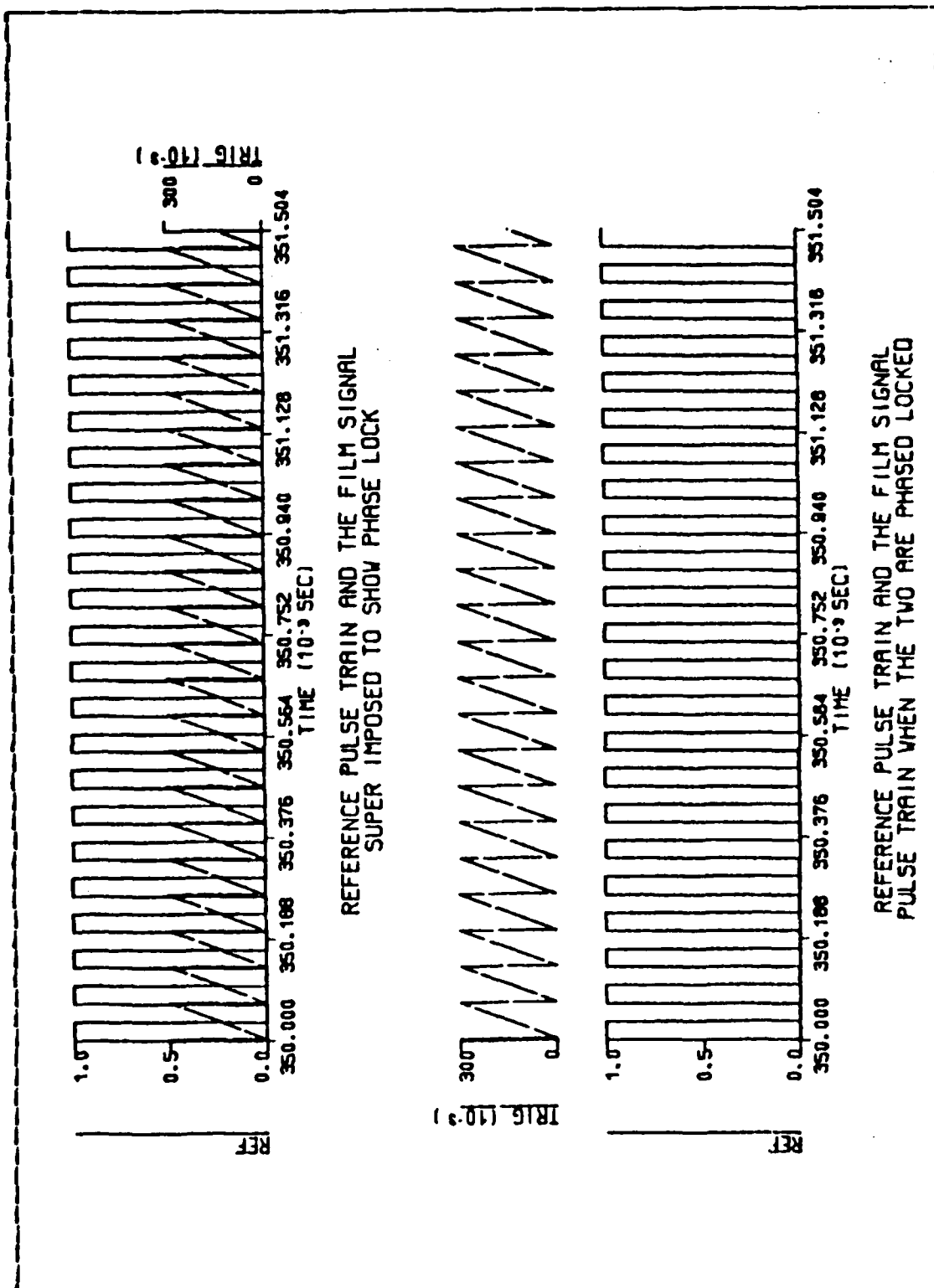
Figure 5.4   Comparison of Take Up Reel Pulse Trains at Lock

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per second. These results are even more significant because the velocity error portion of the system is using the 80% duty cycle pulses that worked so poorly on the supply reel.

The phase locked loop speed control was then tested in the complete camera program. The take up reel is phase locked to the reference signal and the supply reel is phased locked to the take up reel. Again the results at the take up reel are excellent (Figure 5.5), but Figure 5.6 shows that the shutter film speed varies by as much as 4 inches/ sec or 13.3 frames/sec. However, the pulse trains shown in Figures 5.7 and 5.8 show the signals in phase lock. Since the two figures show the signals at two different times it can be seen that the phase relationship between the take up reel and the supply reel has changed, but the two still appear to be frequency locked. A point to note is that these simulation runs had to be run in segments due to computer CPU allocation limits. In this case 0.6 seconds of the total run could be done at a time. Therefore the states at the end of each segment were saved. These states were then used to start the next segment of the run. In this program at the beginning of each segment the take up reel phase error experienced a transient that may have caused the phase relationship between the supply reel and the take up reel to change. To continue the discussion of the results the regulation is not as good as anticipated and this appears to be caused by the fluctuations in the supply reel speed caused by the tension loop signal. Figures 5.9 and 5.10 show the shutter film velocity and the loop tension over the whole run.

The next part of the phase locked loop simulation studies involved incorporating the pretensioning and the deceleration phases into the program. The results are good and reflect the results obtained earlier. During pretensioning the tension is higher than the reference due to the
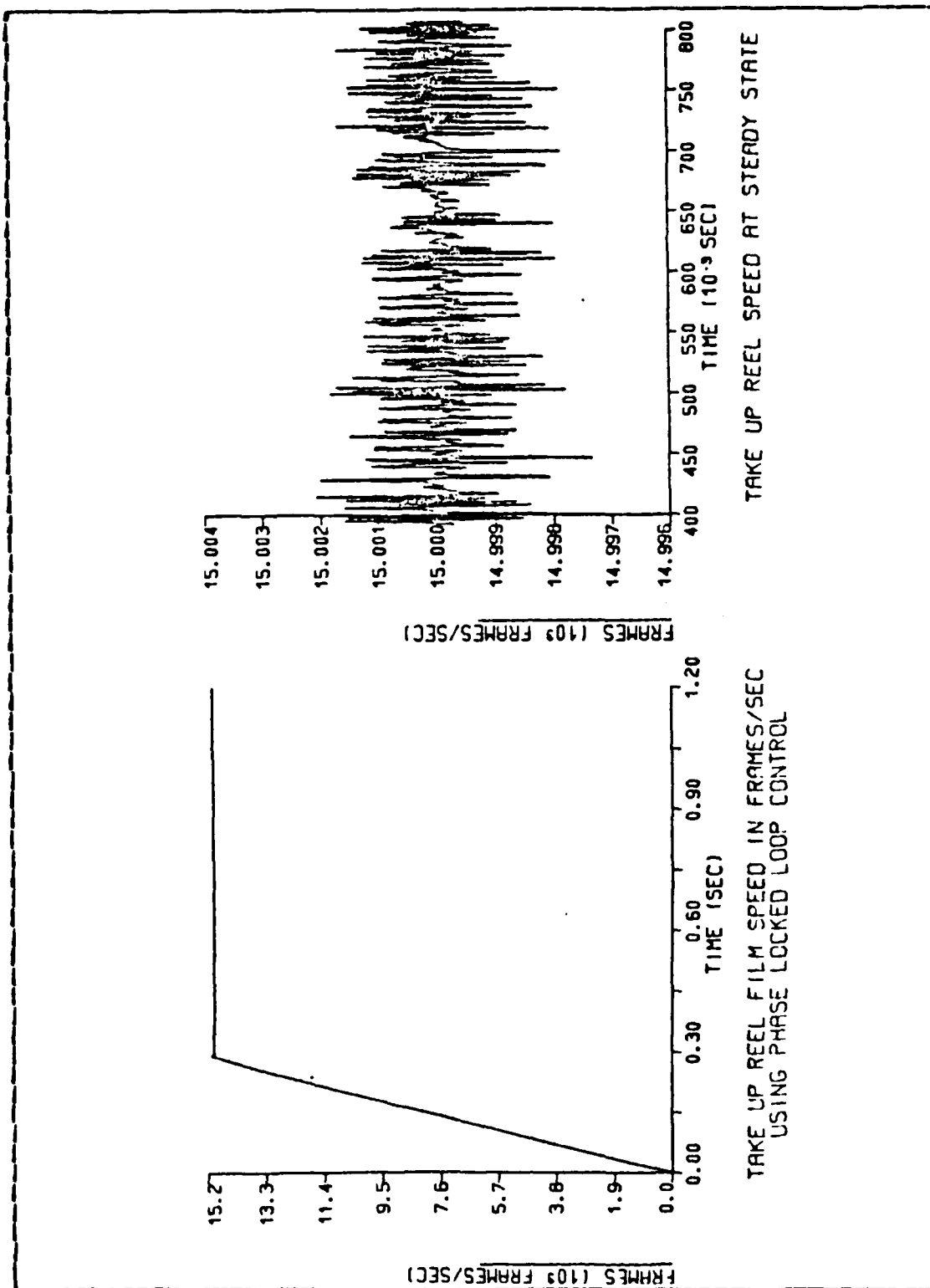
Figure 5.5   Take Up Reel Film Speed

102
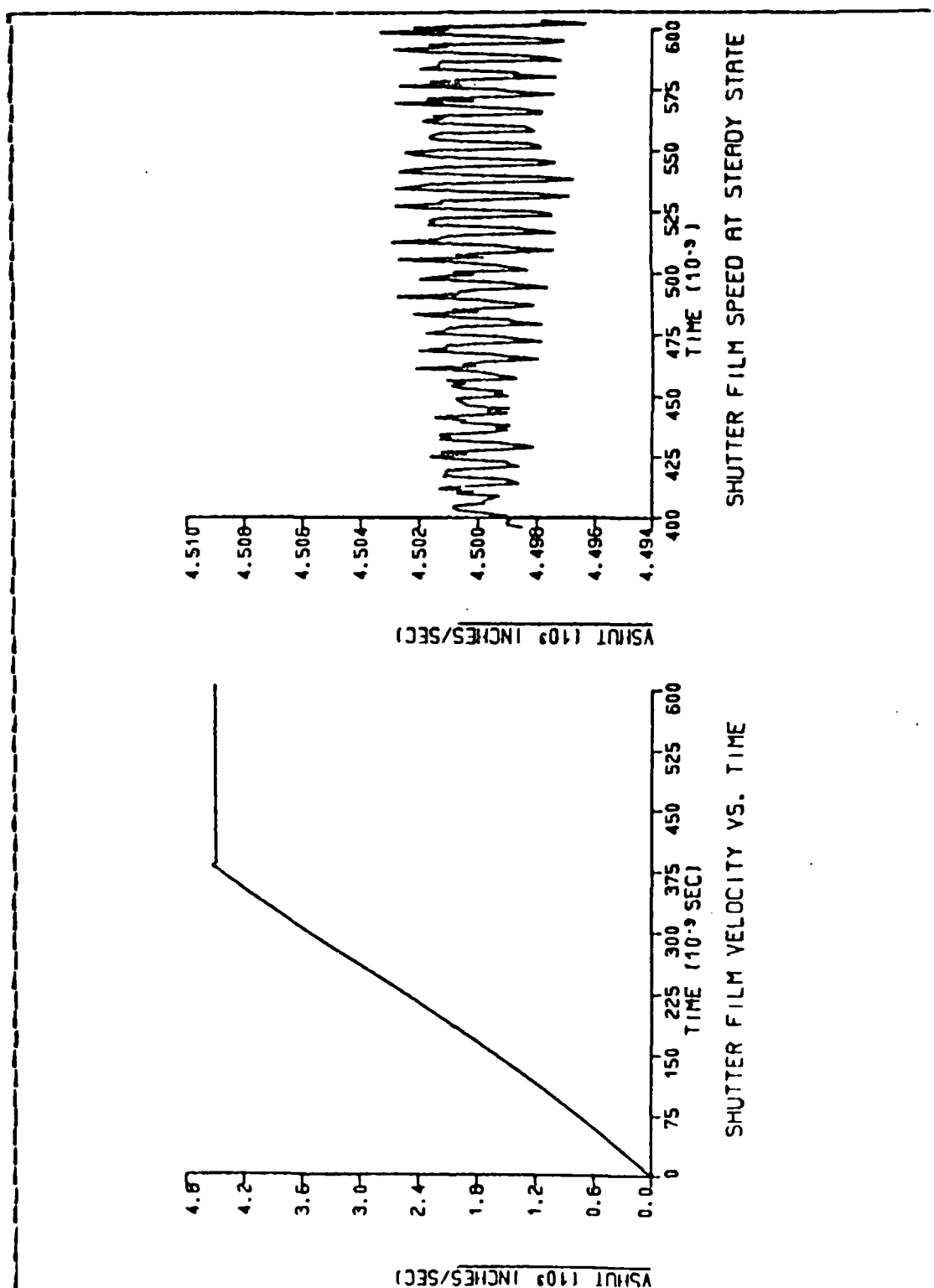
Figure 5.6   Shutter Film Speed for PLL Control

103
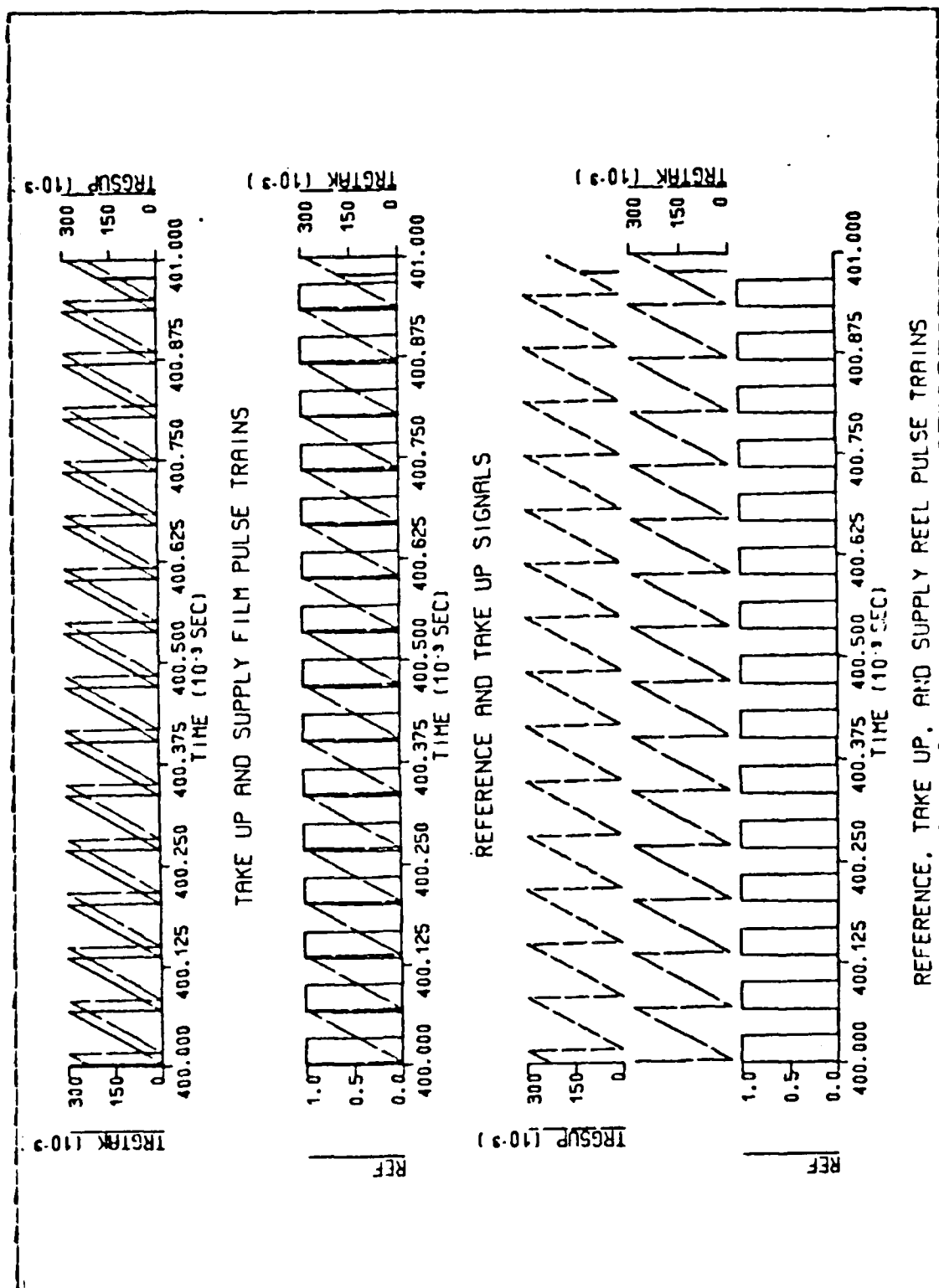
Figure 5.7   Phase signals 0.4 to 0.401 Seconds
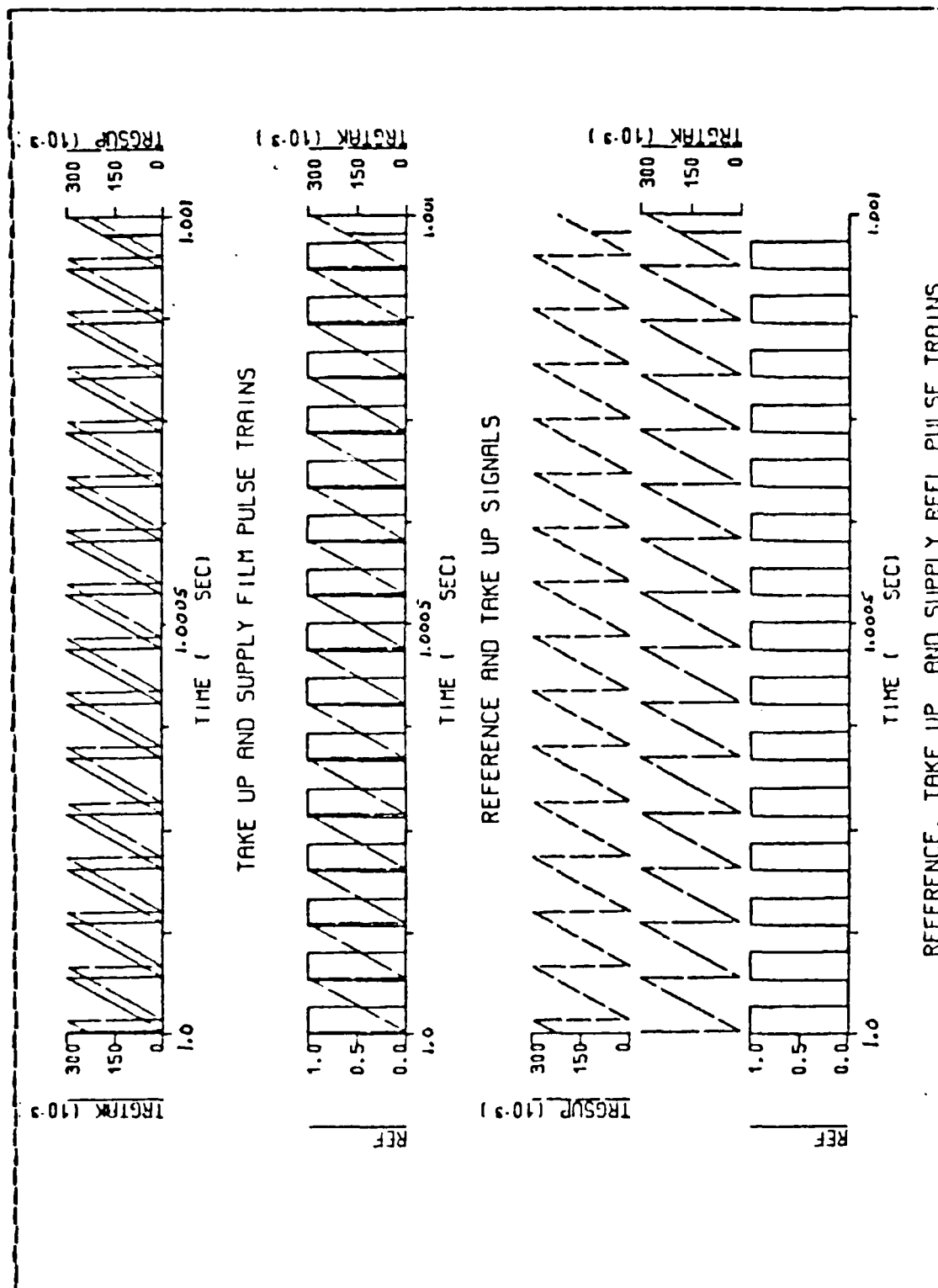
Figure 5.8   Phase Signals 1.0 to 1.001 Seconds
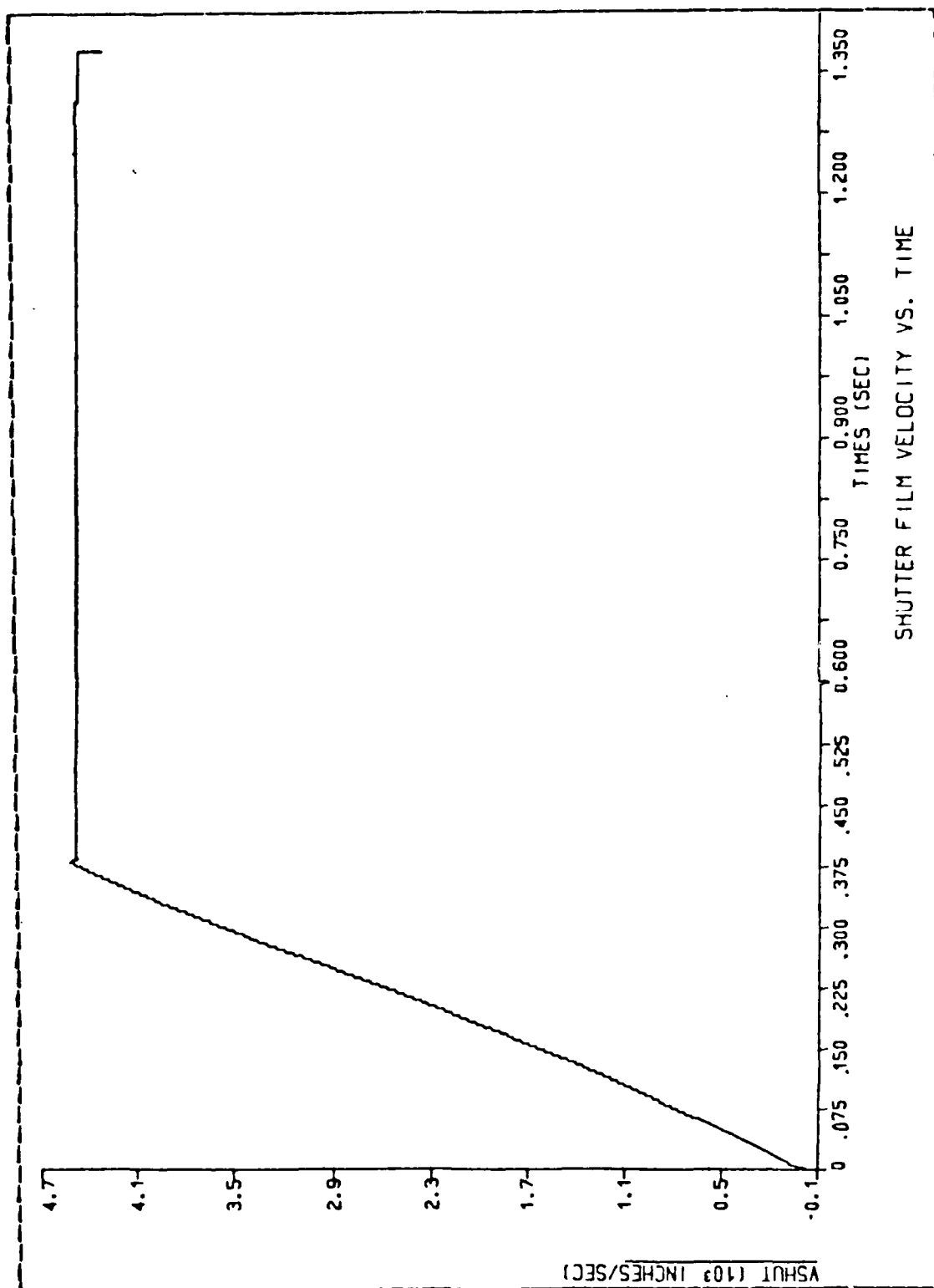
Figure 5.9   Shutter Film Speed with PLL Control

106
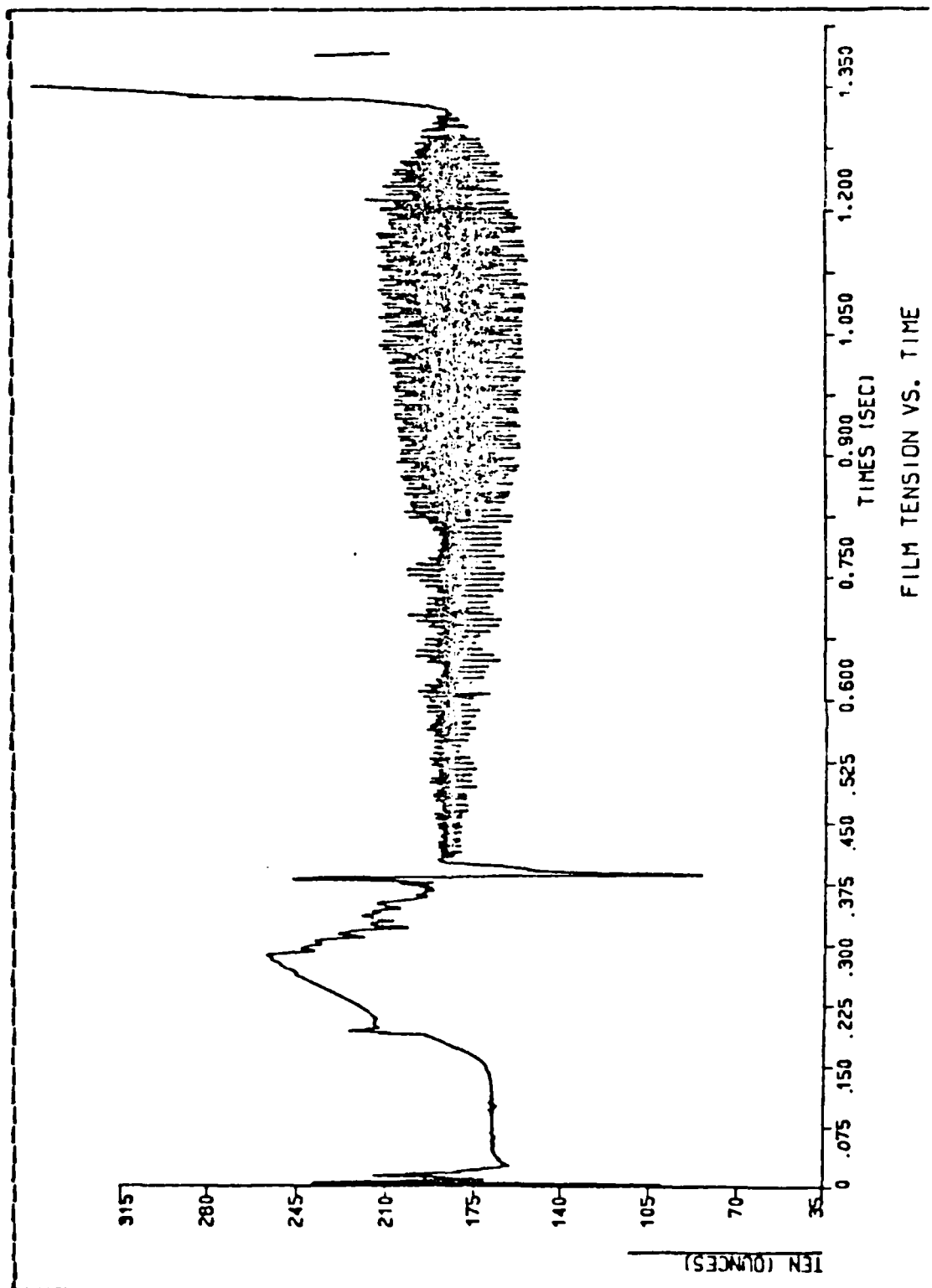
Figure 5.10   Tension for Complete Run

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phase error signal (Figure 5.11). Since only one reel is moving the phase signal is unreliable and in this case acts as a bias offset which is added to the reference signal. Because of this the 16 oz reference has a constant 50 added to it tc create a 66 oz reference signal. However, this does not affect system performance and the steady state results are similar. Figures 5.12 and 5.13 show the shutter film speed and loop tension for the entire run. The pulse trains are shown in Figures 5.14 - 5.16 for different times during the simulation.

The last part of the phase locked loop studies looked at modifications to the control system to get better film speed regulation at the shutter. One method was to move the optical tachometer from the take up reel to the shutter. In this case the film speed fluctuations became even greater because the take up reel speed was no longer locked. This meant that the speed of the film on either side of the shutter was varying and the speed at the shutter was just as erratic. The fluctuations were as much as 18 inches/sec. Another idea was to shcrten the distance between the take up reel and the shutter. This has the effect of stiffening the spring in the connecting length of film. In this case the results were better, but not a great deal better. The improvement was from + 4 inches/sec to + 3 inches/sec which may or may not be important enough to warrant a redesign of the physical relationship of the components in the camera.

Another idea was to phase lock the take up reel to the reference signal and drive the supply reel with the tension loop error signal alone. The first attempt to do this involved no system modifications and was not satisfactory so a transfer function was derived and an open loop bode diagram was drawn (Figure 5.18). The supply reel tension loop transfer function is shown in block diagram form in Figure 5.17 . From the bode diagram the system is seen to
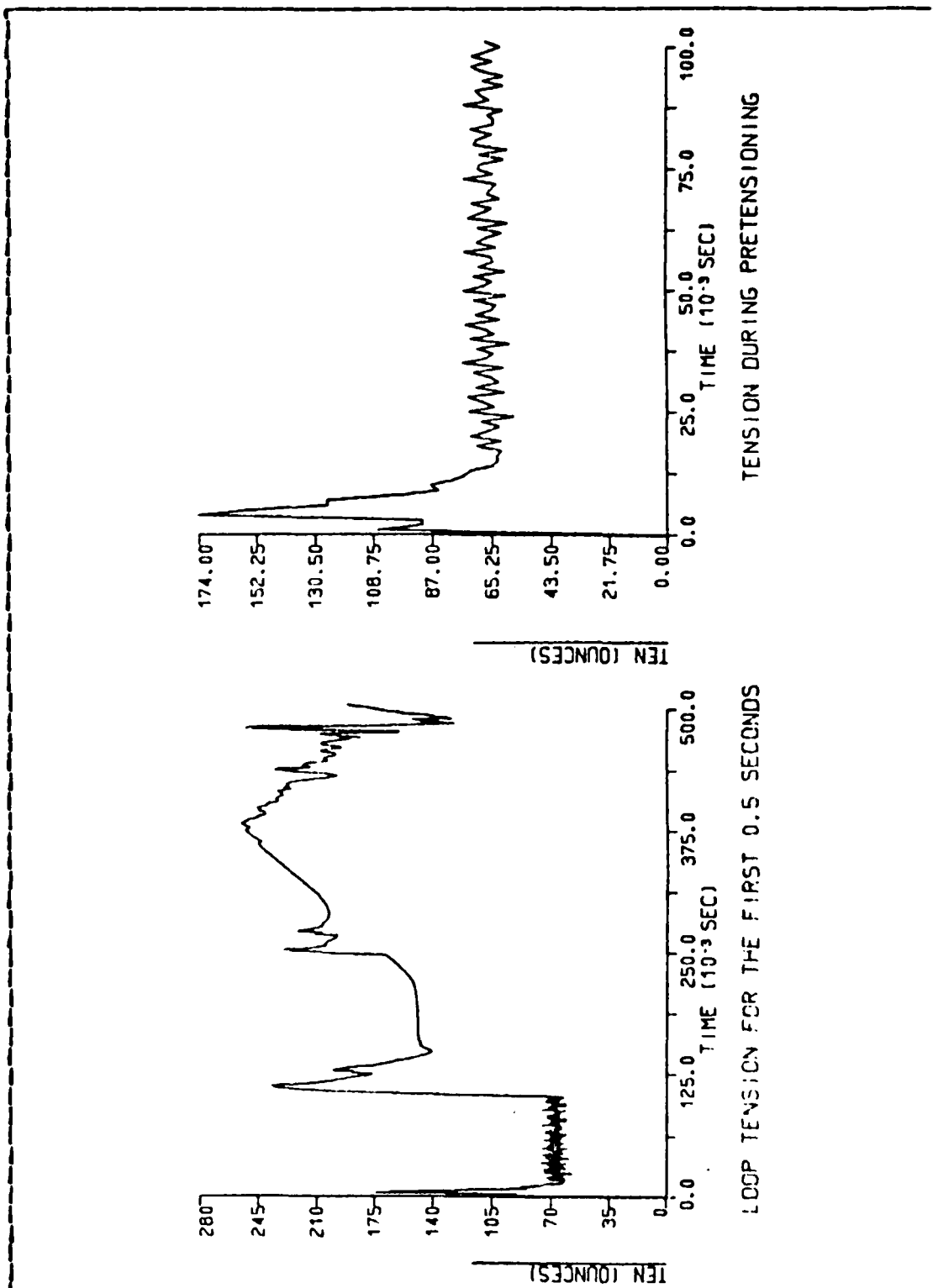
Figure 5.11   Loop Tension During Pretensioning
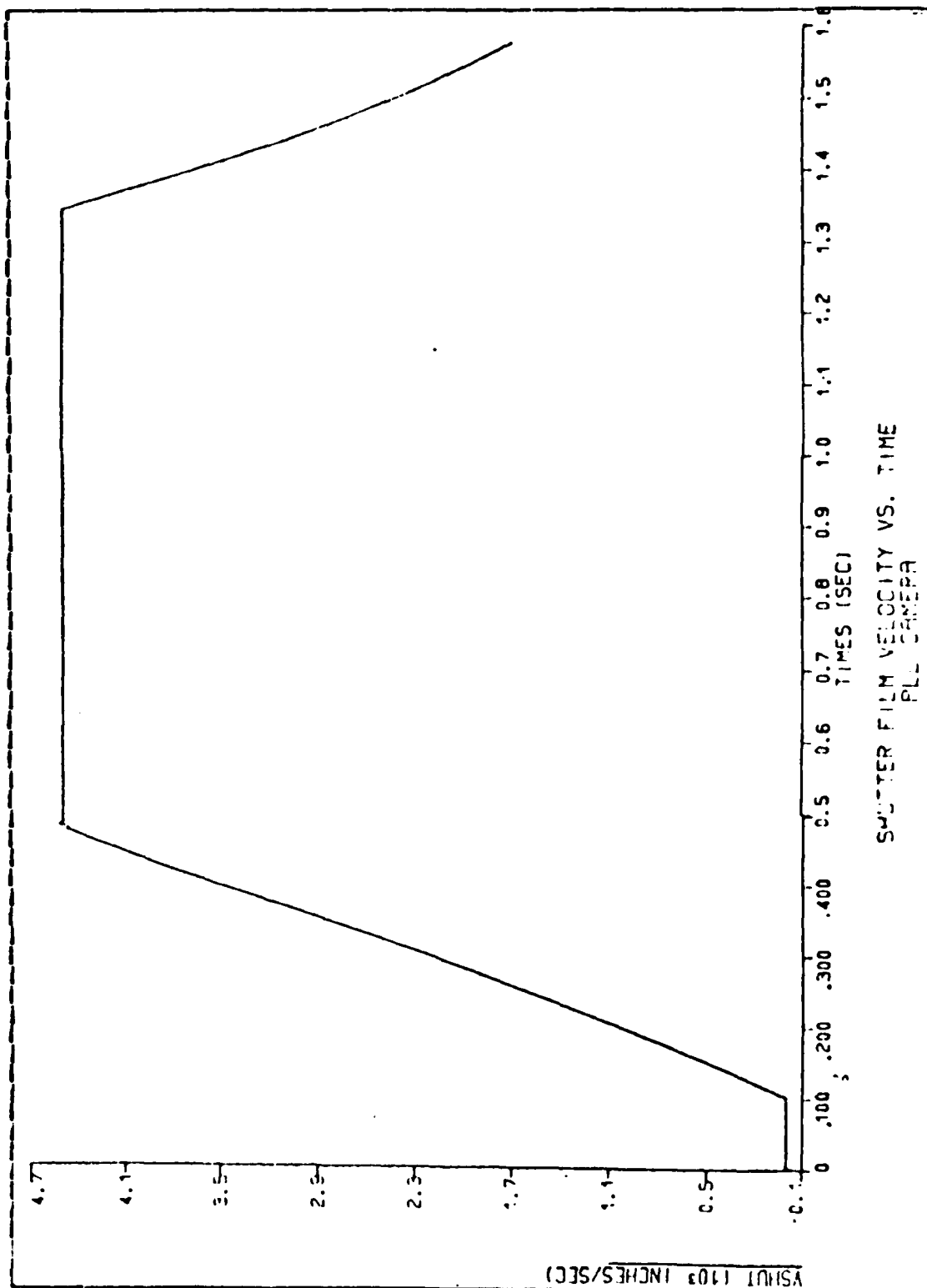
Figure 5.12   Shutter Film Speed: Complete Camera
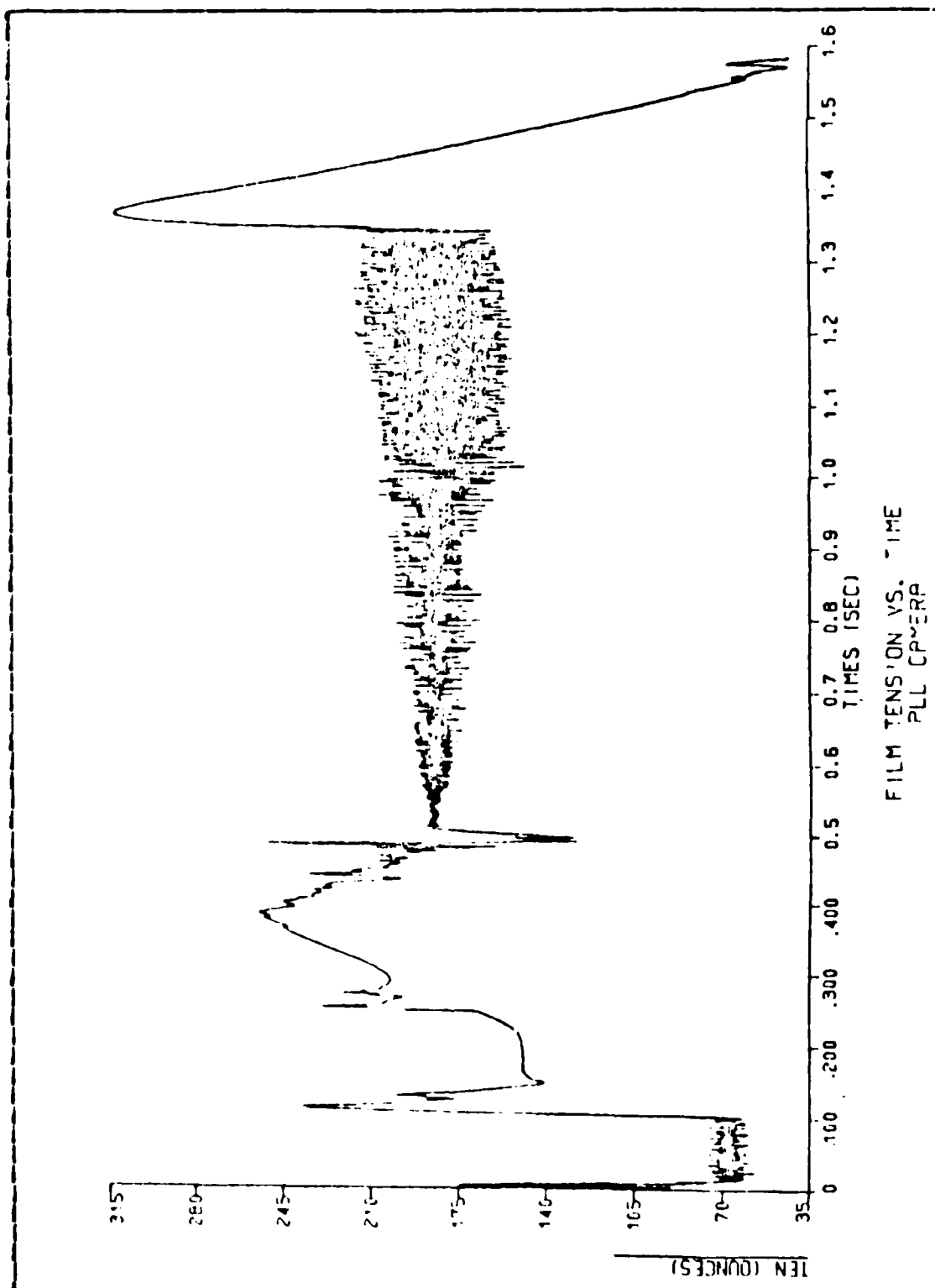
Figure 5.13   Loop Tension: Complete Camera

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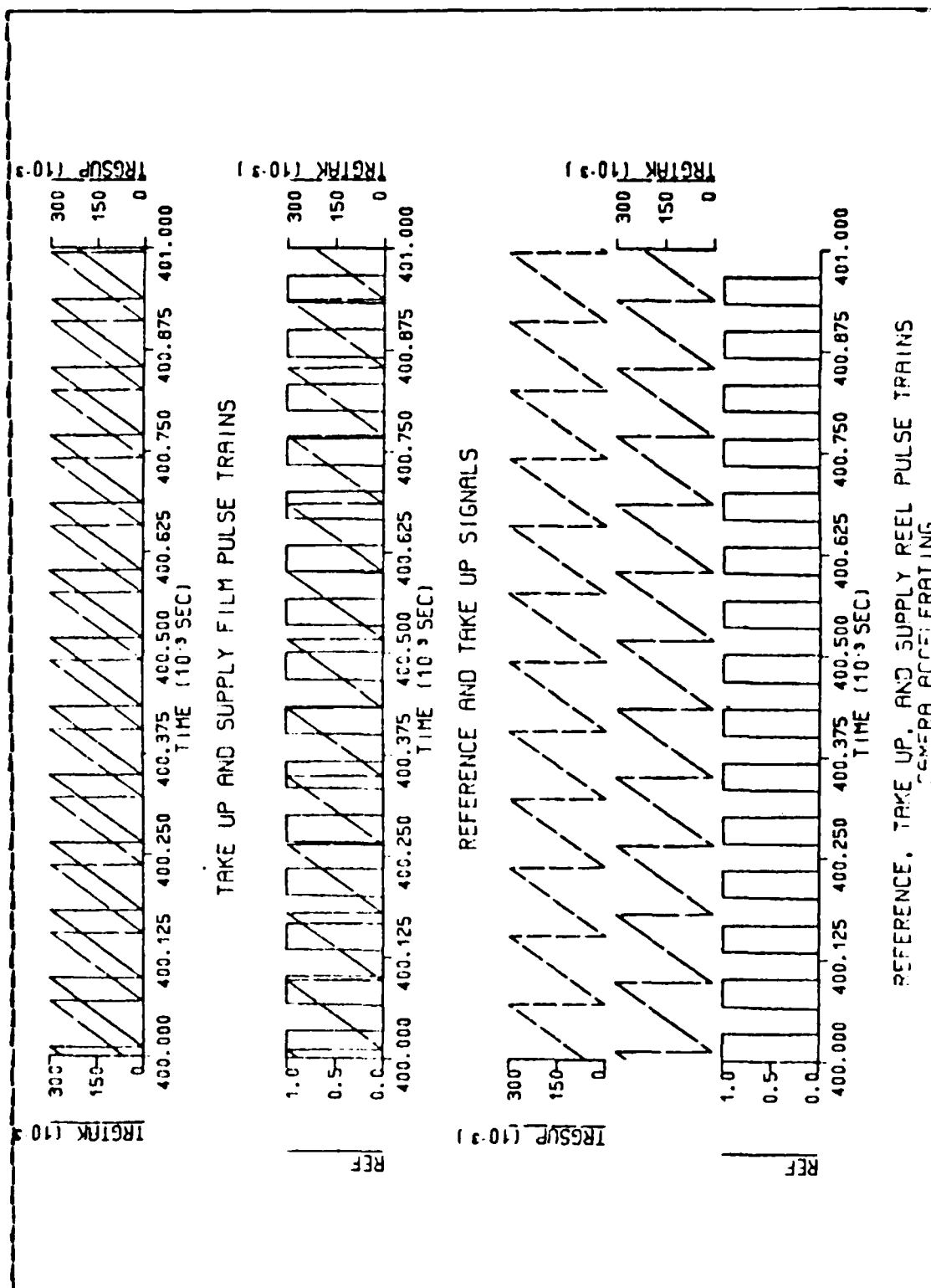
Figure 5.14   Pulse Trains during Acceleration

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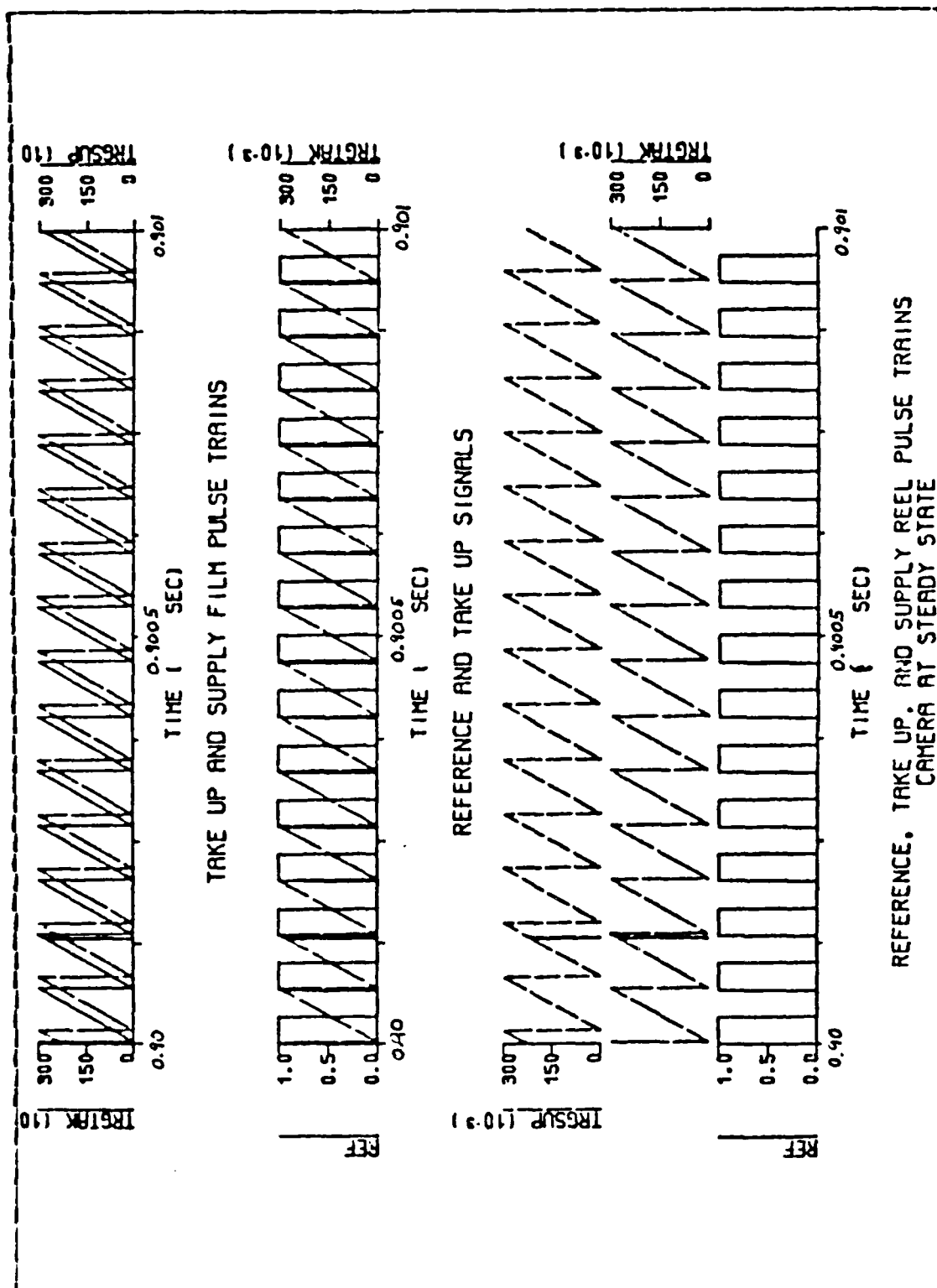
Figure 5.15   Pulse Trains at Steady State

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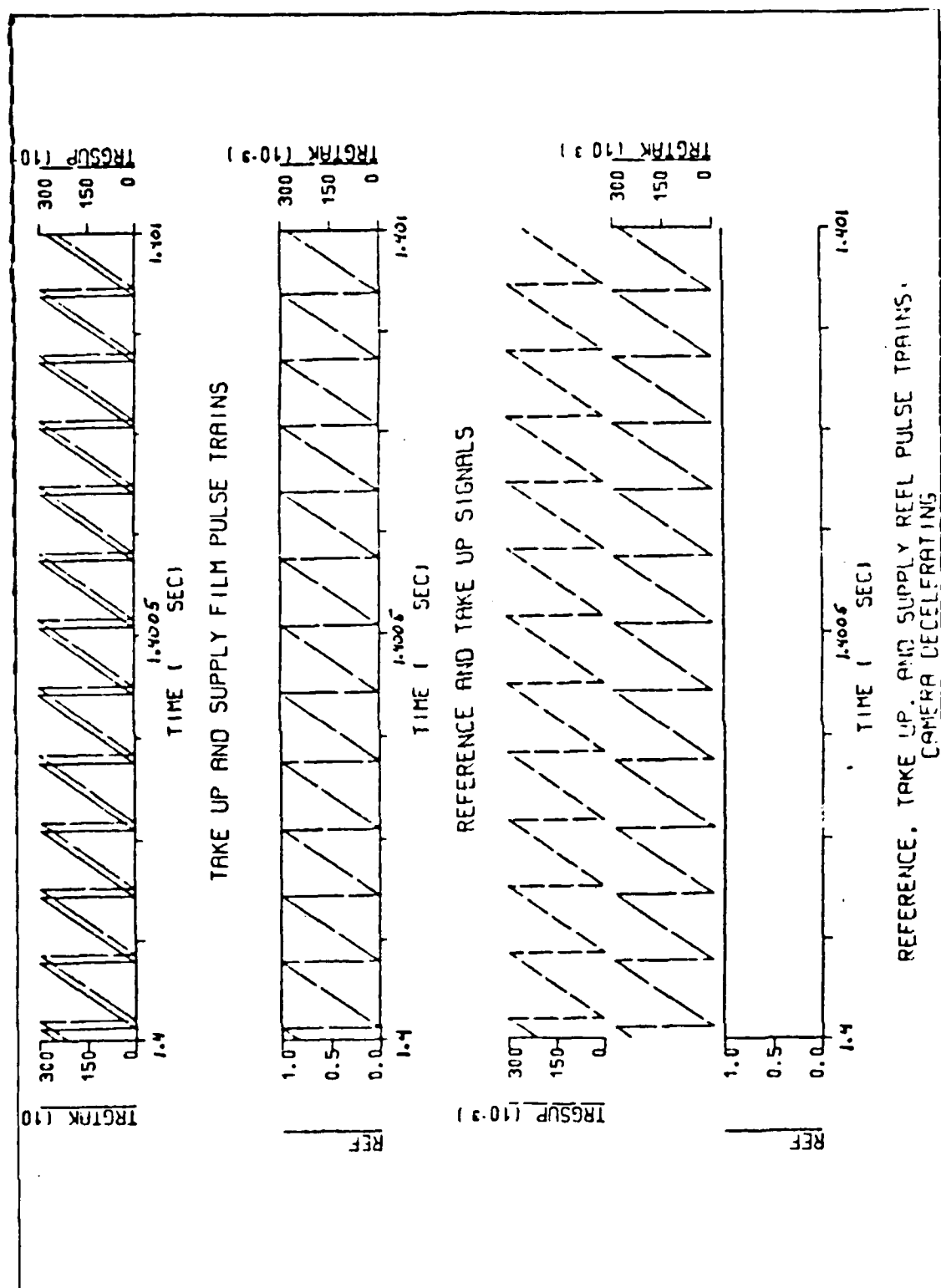
Figure 5.16   Pulse Trains during Deceleration

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be unstable, so a compensater was designed to stabilize the
tensicn loop.
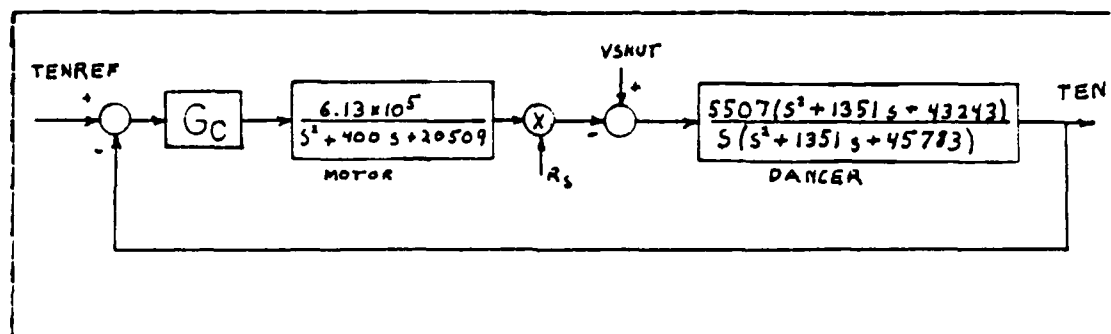
Figure 5.17   Supply Reel Tension Loop Block Diagram

The Bode diagram shows that the phase margin for the
uncompensated system is -80 degrees and the loop is
unstable. Since this is very close to 90 degrees, the
maximum phase shift of a one section lead compensator, it is
apparent that a two section compensator is needed. Also, due
to the phase-gain relationship at least one section will
have to be a lead network. For simplicity it was decided to
make both sections of the compensator lead networks. The
first section was designed to bring the phase margin as
close to zero degrees as possible so that there would be
more latitude in the design of the second section of the
compensator. The compensator design (equation 5.1) gave
plenty of phase margin at the original gain crossover
frequency, but the gain crossover was shifted to a higher,
unstable frequency (Figure 5.19). To correct this the open
loop gain was adjusted to make the gain crossover the same
as for the uncompensated system. The attenuation needed to
do this made the supply reel response and therefore the
system response too slow. Simulation showed that the time to
reach steady state had increased 0.1 seconds over the

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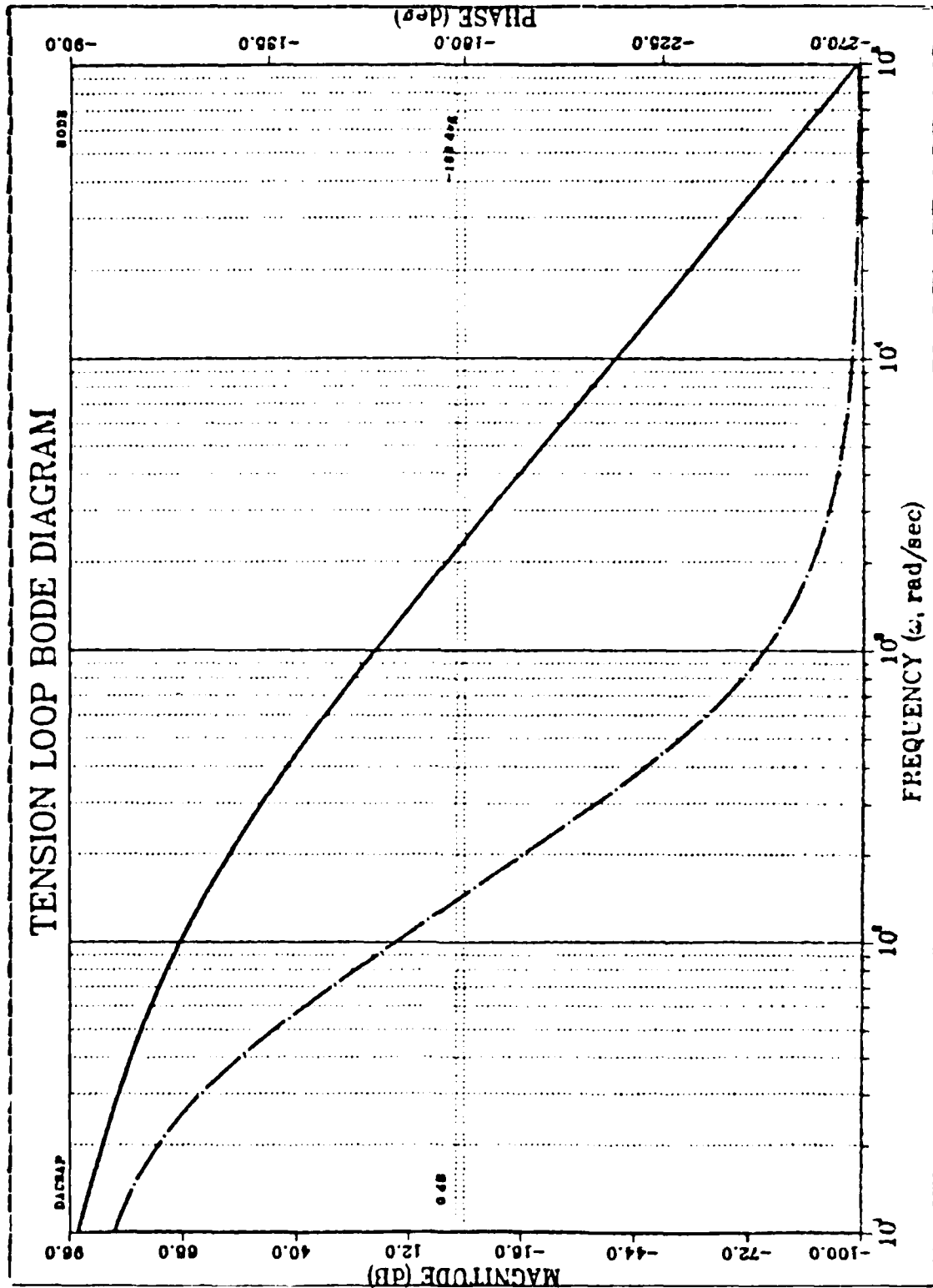
Figure 5.18   Bode Diagram of
Uncompensated Tension Loop

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previously obtained results. In order to speed up the system the open loop gain was increased to 0.1. This reduced the phase margin, but the system was still stable (Figure 5.20). Using this gain value the system response is the same as (0.4 seconds) for the phase locked loop camera design tested earlier. The take up reel frequency locks with the reference signal and the supply reel runs smoothly on the tension signal.

$$G\ (s) = \frac{\frac{S}{20} + 1}{\frac{S}{100,000} + 1}\ \frac{\frac{S}{1000} + 1}{\frac{S}{100,000} + 1} \qquad (5.1)$$

Since the tension is not fluctuating as much and the supply reel speed is smoother, the film speed at the shutter is much smoother (Figure 5.21). The data from the simulation shows a maximum fluctuation of 1 in/sec or 3.3 frames/sec for an ordered speed of 15,000 frames/sec. The shutter speed and the loop tension for the first 0.6 seconds are shown in Figures 5.21 and 5.22 . The program listing for this system is contained in Appendix D.

The preceding discussion of the phase locked loop control shows that for anything but an ideal tachometer speed loop it is a much better system. The speed regulation is excellent, but using two motors can be a problem. The drawback in the system comes from cross coupling between the supply reel speed and tension loops. By removing the speed loop and compensating the tension loop, the cross coupling was eliminated and the speed regulation at the shutter was greatly improved. This system has the added advantage of being much simpler, which means less hardware and therefore fewer parts that can fail.
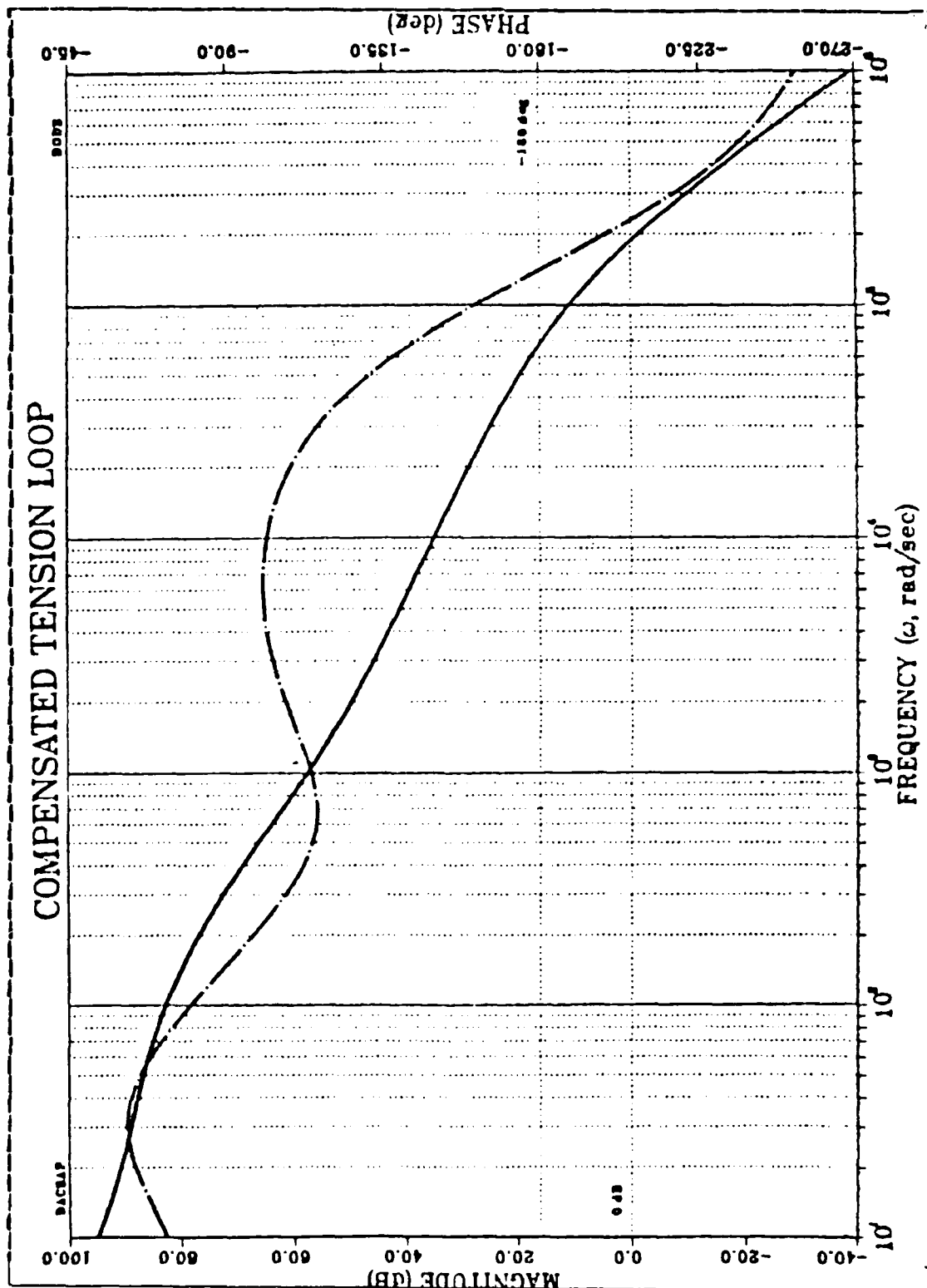
Figure 5.19 Compensated Supply Reel Tension Loop,
Open Loop Gain Equals One

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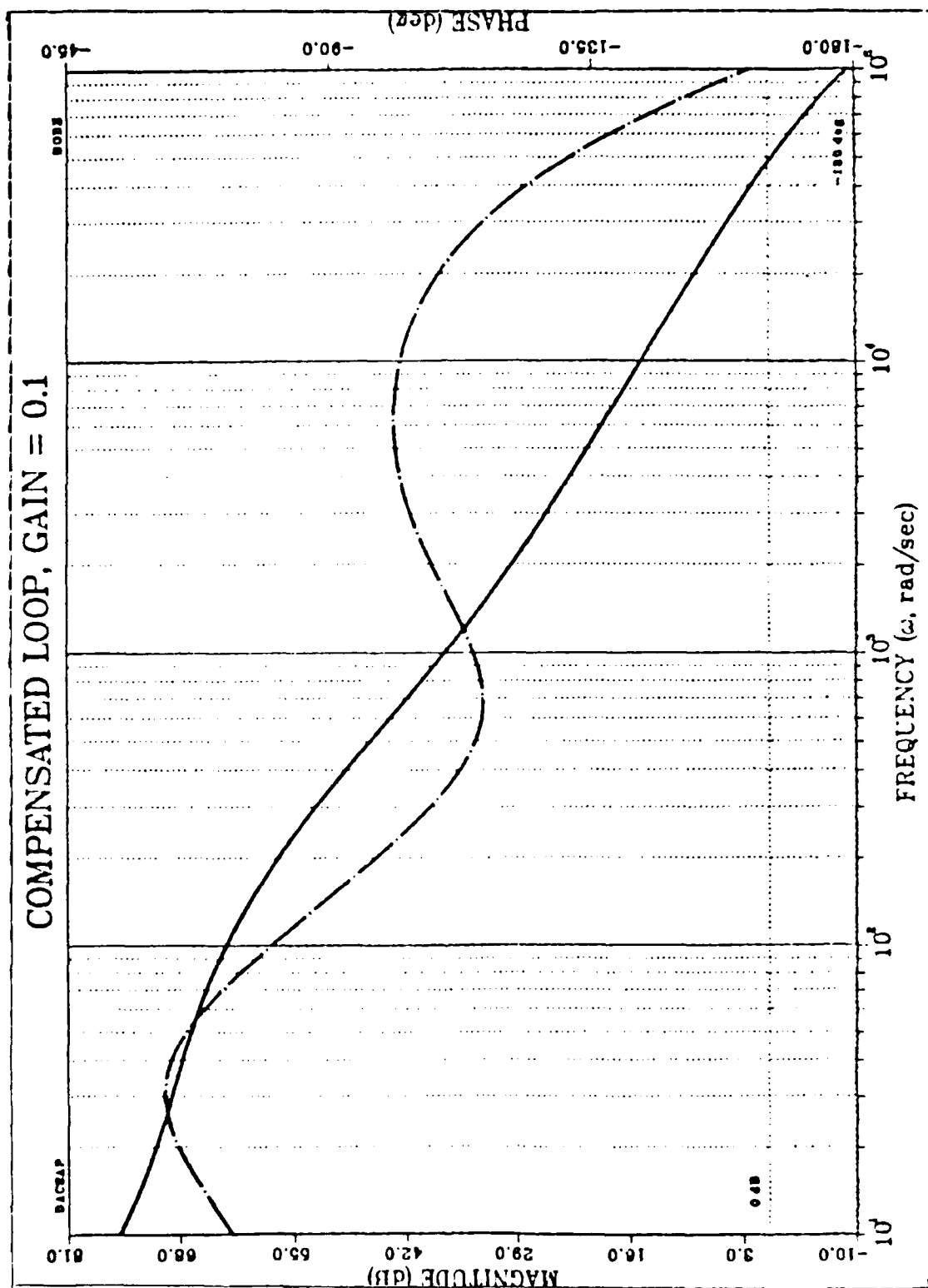
Figure 5.20   Supply Reel Bode Diagram,
Reduced Open Loop Gain

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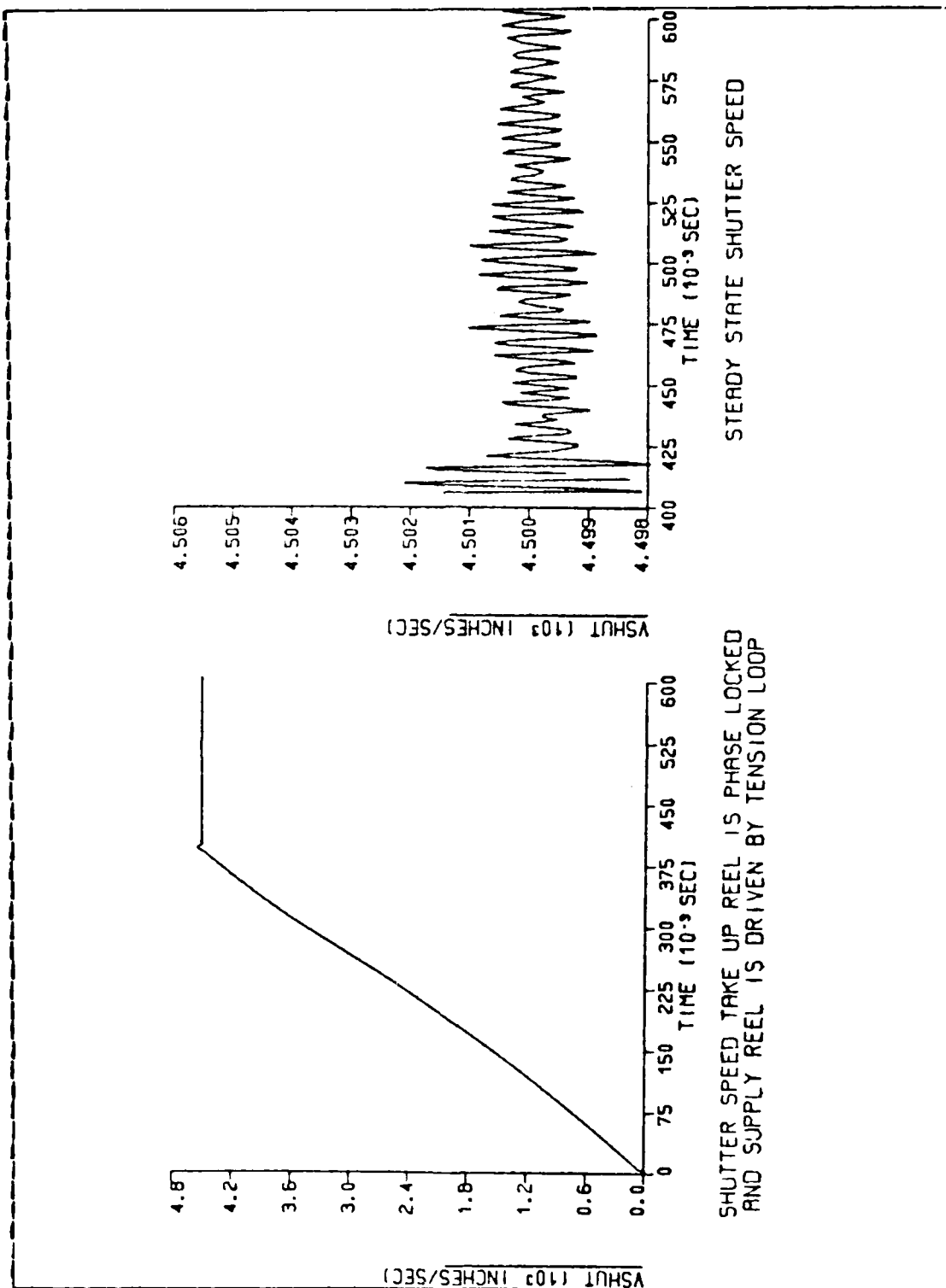
Figure 5.21 Shutter Film Speed: Take Up Reel Phase
Locked and Supply Reel Tension Driven

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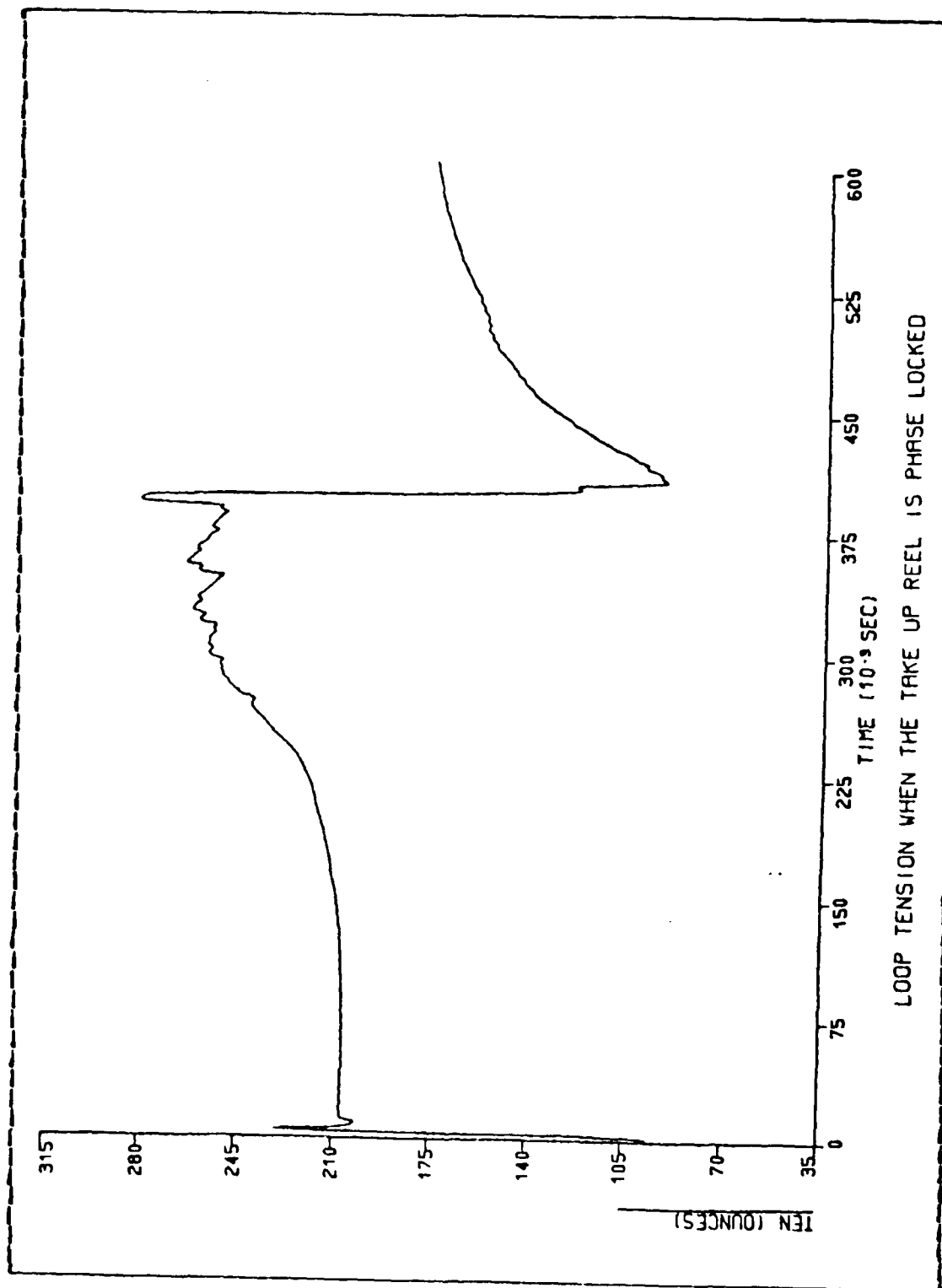
Figure 5.22 Loop Tension: Take Up Reel Phase
Locked and Supply Reel Tension Driven

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VI. DISCUSSION AND CONCLUSIONS

High speed photography has been a useful tool to researchers for a long time and the demand is always for higher and higher frame speeds. To go beyond the present speed of 10,000 frames/sec and still use the same size roll of film, 450 feet, the two motor camera was proposed. This thesis showed that a speed of 15,000 frames/sec was easily reached and that there was at least 312 out of 450 feet of film available to take pictures at steady state.

The results show that the two motors can be successfully controlled so that they work in harmony. The ideal tachometer speed loop showed what was possible and gave realistic goals to aim for when looking at non-ideal system results. The ideal speed loop results showed that the goals of 50 feet of film used during acceleration and 50 feet of film used during deceleration could not be reached with this motor. However the system used only 80 feet during acceleration and 58 feet during deceleration. These results are considered very good.

The use of an optical tachometer and the associated processing showed the real world problems that must be faced. The problem of steady state error had to be solved by increasing the pulse widths and raising the reference signal frequency. The methods of pretensioning and deceleration were examined and a system where the power supply is reversed was chosen. While the results were not as good as the ideal case, the system still performed well enough to be very useful. Here the percent regulation was 0.5%, but the speed of the film at the shutter was not smooth due to coupling between the speed loop and the tension loop.

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A better method of speed control was found in the phase locked loop. Because the phase locked loop raises the system type number, steady state error is eliminated. This controller provided its own stabilization problems, but once overcome the performance improved over the optical tachometer system. With phase locked loop control the film speed at the shutter was regulated to within 4 inches/sec, which is 0.1% regulation. However the shutter film speed was still too erratic so another scheme was investigated.

The problem of shutter film speed variation stemmed from the coupling between the speed loop and the tension loop at the supply reel. To avoid or reduce the amount of coupling the speed loop was removed and the supply reel was driven by the tension loop alone. Once a suitable compensator was designed this method of control produced the best results of all the control methods examined. With this system the shutter film speed regulation was less than 0.03%, which means that the speed did not vary by more than 3 frames/sec.

The final conclusion is that the two motor camera, using a 200 volt pulse width modulated power supply, satisfies the need for a camera that can take pictures at 15,000 frames/sec. The camera accelerates and decelerates fast enough so that a useful amount of film is available to the photographer at the steady state speed. The phase locked loop schemes provide better speed regulation than the optical tachometer, but the optical tachometer control is adequate and the associated circuitry is probably less complicated and less expensive to design and build. In either case the two motor camera has proved that it is a viable concept and that it can be controlled so that the speed regulation at the shutter can be less than 0.03%.

This thesis looked at the problem of reaching 15,000 frames/sec, using as little film as possible during acceleration. While this is higher than most cameras will presently

go, it is not the limit. As higher frame rates are demanded better motors are going to be needed. The torque constant has to increase and the back electromotive force constant has to be small so that the size of the power supply can be kept to a reasonable size. One problem that will have to be faced as frame rates increase is that the lumped parameter model of the DC motor may no longer be valid. At high speeds the inductance of a single armature coil may become significant. This means that a whole new motor model will have to be developed, and that manufacturers are going to have to take this into account when designing very high speed motors.

APPENDIX A
WINDAGE TORQUE CONSTANT DERIVATION

The following is the derivation of the windage torque constant (KW). The formula for the power in Hp required to overcome the losses due to windage is:

$$P(H_p) = 1.5 \times 10^{-17} (W_{RPM})^3 (Dia(in))^5 \tag{A.1}$$

For a reel diameter of 6.5 inches this becomes:

$$P(H_p) = 1.74 \times 10^{-13} (W_{RPM})^3 \tag{A.2}$$

Next convert speed in RPM (W_{RPM}) to speed in rads/sec (W_R)

$$W_{RPM} = (W_R)(rev/2 \cdot \pi \; rads) \cdot (60 sec/min) = W_R \frac{60}{2 \cdot \pi} \tag{A.3}$$

substituting into A.2 yields:

$$P(H_p) = 1.515 \times 10^{-10} (W_R)^3 \tag{A.4}$$

Now convert Hp to oz-in:

$$1 Hp = 550 \; ft\text{-}lbs/sec \quad (12in/ft)(16 \; oz/lb)(1/W_R \; rads/sec) \tag{A.5}$$

$$= \frac{1.056 \times 10^5}{W_R} \; oz\text{-}in \tag{A.6}$$

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The windage torque (T_w) in oz-in is:

$$T_w = \frac{P(H_p) \cdot (1.056 \times 10^5)}{W_R} \qquad \text{(A.7)}$$

$$= \frac{(W_R)^3 (1.515 \times 10^{-10}) \cdot (1.056 \times 10^5)}{W_R} \qquad \text{(A.8)}$$

$$= 0.000016 \cdot (W_R)^2 = KW \cdot (W_R)^2 \qquad \text{(A.9)}$$

APPENDIX B
BLOCK DIAGRAMS AND PROGRAM LISTINGS FOR CHAPTER 3

Figure B.1   System Block Diagram: Take Up Reel follows the
Supply Reel, Tension Loop Signal to Take Up Reel

Figure B.2   System Block Diagram: Supply Reel follows the
Take Up Reel, Tension Loop Signal to Supply Reel

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```
CONST JO = .090984,KTS=3.6800,TAU=.000250,R2=3.25,R=1.0625
CONST W=0.620,H=.0055,KBEMF=0.0334230,KE=2.500,JM=0.0060
CONST BS=0.000143,KD=10.,KSPRIN=320.,MDAN=.0074,RHO=0.00331
PARAM VS=200.0,REF=1500.,TENREF=40.0,KTEN=.5,KTAKSH=3609.
PARAM JSHUT=.001344,RADSH=0.63,OFFSET=0.2538,KSUPSH=5507.
INTGER N,A,NPLOT
PARAM A=0,N=1,NPLOT=1
****
**** THE FOLLOWING IS A LIST OF THE CONSTANTS
**** AND THEIR DIMENSIONS
****
**** JM -MOTOR MOMENT OF INERTIA (IN-OZ-SEC**2)
**** JO- EMPTY REEL MOMENT OF INERTIA (IN-OZ-SEC**2)
**** KTS - MOTOR TORQUE CONSTANT (IN-OZ/AMP**2)
**** KBEMF - BACK EMF CONSTANT (VOLTS/RAD/SEC)
**** W - FILM WIDTH (IN)
**** H - FILM THICKNESS (IN)
**** RHO - FILM DENSITY (OZ/IN**3)
**** R2 - OUTSIDE RADIUS OF REEL (IN)
**** R - INSIDE RADIUS OF REEL (IN)
**** TAU -MOTOR TIME CONSTANT = LM/RM - DIMENSIONLESS
**** KE - MOTOR GAIN CONSTANT =1/RM (MHO)
**** BS - MOTOR DAMPING CONSTANT (IN-OZ/RAD/SEC)
**** KD - DANCER PULLEY DAMPING CONSTANT (OZ/IN/SEC)
**** KSPRIN - DANCER PULLEY SPRING CONSTANT (OZ/IN)
**** MDAN - DANCER PULLEY MASS (SLUGS)
**** KTAKSH - FILM SPRING CONSTANT
*                     (TAKE UP REEL TO SHUTTER) (OZ/IN)
**** KSUPSH - FILM SPRING CONSTANT
*                     (SUPPLY REEL TO SHUTTER) (OZ/IN)
**** JSHUT - SHUTTER MOMENT OF INERTIA (IN-OZ-SEC**2)
**** RADSH - SHUTTER SPROCKET RADIUS (IN)
****
*
INIT
      TEN=40.00
      TENST = 41.00
*******************************************************
*            PULSE WIDTH MODULATION BLOCK
*     THIS BLOCK USES THE INPUT FROM THE ERROR GENERATORS
*     AND COMPARES IT TO THE REFERENCE SIGNAL. THE OUTPUT
*     IS A PULSE THAT IS PROPORTIONAL TO THE ERROR SIGNAL.
*     THE POWER PULSE IS CREATED WHEN THE COMPARITOR PULSE
*     IS USED TO CONTROL A POWER TRANSITOR
*******************************************************
DYNAMIC
      IF (N.EQ.1) VREF =200000.*(TIME - A*.00005)+.0000001
      IF (N.EQ.2) VREF = 10.-200000.*(TIME-A*.00005)
      IF (VREF.GT.0.0.AND.VREF.LT.10.0) GO TO 10
      IF (VREF.LE.0.0) N = 1
      IF (VREF.GE.10.0) N=2
      A = A + 1
  10  CONTINUE
      EAS = 0.0
      IF (VREF.LT.VCOMS) EAS = VS
      IF (IAS.GT.300.0) EAS = 0.0
      EAT = 0.0
      IF (VREF.LE.VCOMT) EAT = VS
      IF (IAT.GT.300.0) EAT = 0.0
      VFILM=REF*STEP (0.)
*
```

```
*
DERIVATIVE
*
**** FILM SPEED ERROR GENERATION: SUPPLY REEL ****
*
      VFILME = VFILMT-VFILMS - TENERR
      DIFF = 100.*VFILME
      VCOMS= LIMIT(0.000,10.0,DIFF)
*
** FILM SPEED ERROR GENERATION: TAKE UP REEL ****
*
      TENERR = TENREF - TEN
      VFLMET= VFILM  - VFILMT
      DIFFT= 100.*VFLMET
      VCOMT= LIMIT(0.0,10.0,DIFFT)
*
*
** ELECTICAL EQUATIONS FOR THE SUPPLY REEL ****
*
      BEMFS = KBEMF*PHIDOT
      IASE = (EAS-BEMFS)*KE
      IAS = REALPL(0.0,TAU,IASE)
      TMS = KTS*IAS
*
** SUPPLY REEL MOMENT OF INERTIA **
*
      RS = R2-(PHI*H/(2.*PI))
      MS = PI*(RS**2-R**2)*W*RHO
      JSFILM = 0.5*MS*(RS**2+R**2)
      JS = JM + JO + JSFILM
*
** CALCULATION OF THE FILM TENSION AND WINDAGE TORQUE ***
*
      TWSUP = .000016*(PHIDOT**2)
      TMSOT = TMS + TLS - TWSUP
*
** CALCULATION OF THE MOTOR ACCELERATION,
** VELOCITY,AND DISPLACEMENT
*
      PHIDDT = (TMS + TLS - TWSUP)/JS -BS*PHIDOT/JS
      PHIDOT = INTGRL(0.0,PHIDDT)
      PHI = INTGRL(0.0,PHIDOT)
*
** CALCULATION OF THE ACTUAL FILM SPEED **
*
      VFILMS = RS * PHIDOT
      LENG = INTGRL(0.0,VFILMS)
      FRAMES= VFILMS/0.3
*
**** TAKE UP REEL EQUATIONS ****
*
** ELECTICAL EQUATIONS FOR THE TAKE UP REEL ****
*
      BEMFT = KBEMF*PSIDOT
      IATE = (EAT-BEMFT)*KE
      IAT = REALPL(0.0,TAU,IATE)
      TMT = KTS*IAT
*
** TAKE UP REEL MOMENT OF INERTIA **
*
      RT = R +(PSI*H/(2.*PI))
      MT = PI*(RT**2-R**2)*W*RHO
      JTFILM = 0.5*MT*(RT**2+R**2) .
      JT = JM + JO + JTFILM
*
```

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```
*
** CALCULATION OF THE FILM TENSION **
*
      TWTAK = .000016*(PSIDOT**2)
      TMTOT = TMT - TLT -TWTAK
*
** CALCULATION OF THE MOTOR ACCELERATION,
** VELOCITY,AND DISPLACEMENT
*
      PSIDDT = (TMT - TLT - TWTAK)/JT -BS*PSIDOT/JT
      PSIDOT = INTGRL(0.0,PSIDDT)
      PSI = INTGRL(0.0,PSIDOT)
*
** CALCULATION OF THE ACTUAL FILM SPEED **
*
      VFILMT = RT * PSIDOT
      LENGT= INTGRL(0.0,VFILMT)
      FRAMET= VFILMT/0.3
*
**** CALCULATIONS CONCERNING THE SHUTTER ASSEMBLY ****
*
      THEDDT=RADSH*(TENST-TEN)/JSHUT
      THEDOT=INTGRL(0.0,THEDDT)
      VSHUT=RADSH*THEDOT
*
***** AMOUNT OF FILM IN THE LOOP *****
*
      VDIFFT=VFILMT-VSHUT
      VDELT=VSHUT-VFILMS
      LOOPST=INTGRL(0.0111,VDIFFT)
      LOOPSS=INTGRL(0.0,VDELT)
      VFILMD = VFILMT - VFILMS
      DELTL = INTGRL(0.0,VFILMD)
*
**** TENSION ROLLER ASSEMBLY AND
**** LOOP TENSION CALCULATIONS
*
      TENST=LOOPST*KTAKSH
      DISPAC = (2.*TEN - KD*DISPVE - KSPRIN*DISTEN)/MDAN
      DISPVE = INTGRL(0.0,DISPAC)
      DISP = INTGRL(-0.0038,DISPVE)
      DISTEN = OFFSET + DISP
      TEN = KSUPSH*(LOOPSS- 2*DISP)
NOSORT
      IF (DISTEN.GE.0.0.AND.DISTEN.LE.2.0) GO TO 30
         DISPVE = 0.0
         DISPAC = 0.0
         DISP   =-(OFFSET)
         IF (DISTEN.LT.1.0) GO TO 30
         DISP   = 2.0 - OFFSET
         TEN = KSUPSH*(LOOPSS- 2*DISP)
   30 CONTINUE
      IF (TEN.LT.0.0) TEN = 0.0
      IF (TENST.LT.0.0) TENST = 0.0
SORT
FINISH  RT = 3.25,RS=1.0625,LENG =5400.
METHOD TRAPZ
CONTRL FINTIM = 1.00,DELT = 0.000001
SAVE (F1) 0.002 ,VFILMT,VSHUT,LENGT,IAT,VFILMS
SAVE (F2) 0.002,LENG,TEN,TENST,DISTEN
PRINT 0.010,VFILMT,VFILMS,TEN,IAT,IAS,TMTOT,TMSOT,LOOPSS
END
STOP
```

PROGRAM LISTING FOR THE OPTICAL TACHOMETER CAMERA WITH

PRETENSIONING AND DECELERATION

```
CONST JO = .090984,KTS=3.6800,IAU=.000250,R2=3.25,R=1.0625
CONST W=0.620,H=.0040,KBEMF=0.0334230,KE=2.500,JM=0.0060
CONST BS=0.000143,KD=10.,KSPRIN=320.,MDAN=.0074,RHO=0.00331
PARAM VS=200.0,TENREF=160.,KTEN=.5,KTAKSH=3609.,KSUPSH=5507
PARAM JSHUT=.001344,RADSH=0.63,VFILMR=94342.12,DUR=.000066
INTGER N,A,NPLOT,FLAG
PARAM A=0,N=1,NPLOT=1,OFFSET=0.000
****
**** THE FOLLOWING IS A LIST OF THE CONSTANTS
**** AND THEIR DIMENSIONS
****
**** JM -MOTOR MOMENT OF INERTIA (IN-OZ-SEC**2)
**** JO- EMPTY REEL MOMENT OF INERTIA (IN-OZ-SEC**2)
**** KIS - SUPPLY MOTCR TORQUE CONSTANT (IN-OZ/AMP**2)
**** KBEMF - BACK EMF COMSTANT (VOLTS/RAD/SEC)
**** W - FILM WIDTH (IN)
**** H - FILM THICKNESS (IN)
**** RHC - FILM DENSITY (OZ/IN**3)
**** R2 - OUTSIDE RADIUS OF REEL (IN)
**** R - INSIDE RADIUS OF REEL (IN)
**** IAU -MOTOR TIME CONSTANT = LM/RM - DIMENSIONLESS
**** KE - MOTOR GAIN CONSTANT =1/RM (MHO)
**** BS - MOTOR DAMPING CONSTANT (IN-OZ/RAD/SEC)
**** KD - DANCER PULLEY DAMPING CONSTANT (OZ/IN/SEC)
**** KSPRIN - DANCER PULLEY SPRING CONSTANT (OZ/IN)
**** MDAN - DANCER PUILEY MASS (SLUGS)
**** KTAKSH - FILM SPRING CONSTANT
*                 (TAKE UP REEL TO SHUTTER) (OZ/IN)
**** KSUFSH - FILM SPRING CONSTANT
*                 (SUPPLY REEL TC SHUTTER) (OZ/IN)
**** JSHUT - SHUTTER MOMENT CF INERTIA (IN-OZ-SEC**2)
**** RADSH - SHUTTER SPROCKET RADIUS (IN)
****
INITIAL
      OMEGAR = 0.0
      PASOME = 0.0
      FLAG = 0
      OMEGAD = VFILMR
DYNAMIC
*****************************************************************
*
*    This section of the program checks to see if the film
*  is accelerating, decelerating, or steady
*
*****************************************************************
      OMEGAR = VFILMR*(STEP(0.1))
      IF(LENG.GT.4700.) OMEGAR = 0.0
      IF(LENGT.GT.4700.) OMEGAR = 0.0
      IF (OMEGAR.GT.PASOME) FLAG =1
      IF (OMEGAR.LT.PASOME) FLAG = 0
      PASOME = OMEGAR
```

```
**********************************************************
*
*     This section of the program creates the film pulse
*  trains and extracts the velocity and position infor-
*  mation from them. This information is used to make the
*  error signals which are the input to the PWM.
*
**********************************************************
*
**  FILM SPEED ERROR GENERATION: TAKE UP REEL ****
*
      SET = 0.0
      IF (Y1.GE.0.0) SET = 1.0
      TENREF = 160.0
      IF (FLAG.EQ.0) TENREF = 16.0
      TENERR = TENREF - TEN
      TRGTAK = AMOD(LENGT,0.3)
      TRGTK1= 0.0
      IF (TRGTAK.GE.0.15) TRGTK1 = 1.0
      TRGTK2= 0.0
      IF (TRGTK1.GT.PASTK1) TRGTK2 = 1.
      TAKPLS = PULSE(TRGTK2,DUR)
      SIGTAK = INTGRL(0.0000299,TAKPLS)
      REF = 0.0
      REF1= 0.0
      IF (Y.GE. 0.00) REF = 1.0
      IF (FLAG.EQ.0) REF = 0.0
      IF (REF.GT.PASREF) REF1=1.0
      REF2 = PULSE(REF1,DUR)
      DIFF = REF - TRGTK1
      OPT = INTGRL(0.0000000,REF2)
      TAKDIF = INTGRL(-0.0000177,DIFF)
      IF (SET.LE.PASSET) GO TO 40
         VOPT = OPT
         VSGTAK = SIGTAK
         OPT = 0.0
         SIGTAK = 0.0
         TAKDIF = 0.0
 40   CONTINUE
      VETAK = VOPT - VSGTAK
      VFMTAK = 50000000.*VETAK
      FINET=100000.*TAKDIF
      VCOMT= LIMIT(0.0,10.0,VFMTAK)
      IF (FLAG.EQ.0) VCOMT= LIMIT(0.0,10.0,-(VFMTAK))
*
**** FILM SPEED ERROR GENERATION: SUPPLY REEL ****
*
      TRGSUP = AMOD(LENG ,0.3)
      TRGSP1= 0.0
      IF (TRGSUP.GE.0.15) TRGSP1 = 1.0
      TRGSP2= 0.0
      IF (TRGSP1.GT.PASSP1) TRGSP2 = 1.
      SUPPLS = PULSE(TRGSP2,DUR)
      SIGSUP = INTGRL(0.0000566,SUPPLS)
      SIGREF = INTGRL(0.0000660,TAKPLS)
      DIFFS = TRGTK1 - TRGSP1
      SUPDIF = INTGRL(0.0000094,DIFFS)
      IF (TRGTK1.LE.PASTK1) GO TO 50
         VSGSUP = SIGSUP
         VSGREF = SIGREF
         SIGREF = 0.0
         SIGSUP = 0.0
         SUPDIF = 0.0
 50   CONTINUE
      VESUP = VSGREF - VSGSUP
      VFMSUP = 50000000.*VESUP
      FINES=100000.*SUPDIF
```

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```
      VCOMS= LIMIT(0.0,10.0,VFMSUP-TENERR)
      IF (FLAG.EQ.0) VCOMS= LIMIT(0.,10.,-(VFMSUP-TENERR))
      PASREF = REF
      PASSET = SET
      PASTK1 = TRGTK1
      PASSP1 = TRGSP1
*
*
*************************************************************
*    This block uses the input from the error block and
*  compares it to the reference signal to create the
*  power pulse TRAIN which drives the motor
*************************************************************
      IF (N.EQ.1) VREF =200000.*(TIMES- A*.00005)+.0000001
      IF (N.EQ.2) VREF = 10.-200000.*(TIMES-A*.00005)
      IF (VREF.GT.0.0.AND.VREF.LT.10.0) GO TO 10
      IF (VREF.LE.0.0) N = 1
      IF (VREF.GE.10.0) N=2
      A = A + 1
  10  CONTINUE
      EAS = 0.0
      IF (VREF.LT.VCOMS) EAS = VS
      IF (IAS.GT.300.0) EAS = 0.0
      EAT = 0.0
      IF (VREF.LE.VCOMT) EAT = VS
      IF (IAT.GT.300.0) EAT = 0.0
      IF (FLAG.EQ.1) GO TO 100
      EAS = 0.0
      IF (VREF.LT.VCOMS) EAS =-VS
      IF (IAS.LT.-300.0) EAS = 0.0
      EAT = 0.0
      IF (VREF.LE.VCOMT) EAT =-VS
      IF (IAT.LT.-300.0) EAT = 0.0
 100  CONTINUE
      IF (OMEGAR.NE.0.0.OR.VFILMT.GE.0.25) GO TO 110
         PSI = 0.0
         PSIDOT = 0.0
         PSIDDT = 0.0
         EAT = 0.0
 110     CONTINUE
*
** ELECTICAL EQUATIONS FOR THE SUPPLY REEL ****
*
DERIVATIVE
      Y = SINE(0.0,OMEGAR,-0.00003635)
      Y1= SINE(0.0,OMEGAD,-0.04625350)
      BEMFS = KBEMF*PHIDOT
      IASE = (EAS-BEMFS)*KE
      IAS = REALPL(-189.77,TAU,IASE)
      TMS = KTS*IAS
*
** SUPPLY REEL MOMENT OF INERTIA **
*
      RS = R2-(PHI*H/(2.*PI))
      MS = PI*(RS**2-R**2)*W*RHO
      JSFILM = 0.5*MS*(RS**2+R**2)
      JS = JM + JO + JSFILM
*
** CALCULATION OF THE TORQUE DUE TO
** FILM TENSION AND WINDAGE
*
      TLS = TEN * RS
      TWSUP = 0.000016*(PHIDOT**2)
*
```

```
**  CALCULATION OF THE MOTOR ACCELERATION,
**  VELOCITY,AND DISPLACEMENT
*
      PHIDDT = (TMS + TLS - TWSUP)/JS -BS*PHIDOT/JS
      PHIDOT = INTGRL(1417.8,PHIDDT)
      PHI = INTGRL(2016.8,PHIDCT)
*
**  CALCULATION OF THE ACTUAL FILM SPEED  **
*
      VFILMS = RS * PHIDOT
      LENG = INTGRL(5259.7,VFILMS)
      FRAMES= VFILMS/0.3
****
*
****  TAKE UP REEL EQUATIONS ****
*
**  ELECTICAL EQUATIONS FOR THE TAKE UP REEL ****
*
      BEMFT = KBEMF*PSIDOT
      IATE = (EAT-BEMFT)*KE
      IAT = REALPL(-300.09,TAU,IATE)
      TMT = KTS*IAT
*
**  TAKE UP REEL MOMENT OF INERTIA **
*
      RT = R +(PSI*H/(2.*PI))
      MT = PI*(RT**2-R**2)*W*RHO
      JTFILM = 0.5*MT*(RT**2+R**2)
      JT = JM + JO + JTFILM
*
**  CAICULATION OF THE TORQUE DUE TO
**  FIIM TENSION AND WINDAGE
*
      TLT = TEN * RT
      TWTAK = .000016*(PSIDOT**2)
*
**  CAICULATION OF THE MOTOR ACCELERATION,
**  VELOCITY,AND DISPLACEMENT
*
      PSIDDT = (TMT - TLT -TWTAK)/JT -BS*PSIDOT/JT
      PSIDOT = INTGRL(996.43,PSIDDT)
      PSI = INTGRL(2725.4,PSIDCT)
*
**  CALCULATION OF THE ACTUAL FILM SPEED **
*
      VFILMT = RT * PSIDOT
      LENGT= INTGRL(5259.9,VFILMT)
      FRAMET= VFILMT/0.3
*
****  CALCULATIONS CONCERNING THE SHUTTER ASSEMBLY ****
*
      THEDDT=RADSH*(TENST-TEN)/JSHUT
      THEDOT=INTGRL(4425.2,THEDDT)
      VSHUT=RADSH*THEDCT
```

```
*
***** AMOUNT OF FILM IN THE LOOP *****
*
      VDIFFT=VFILMT-VSHUT
      VDELT=VSHUT-VFILMS
      LOOPST=INTGRL(-0.00429687,VDIFFT)
      LOOPSS=INTGRL(0.28040,VDELT)
      VFILMD = VFILMT - VFILMS
      DELTL = INTGRL(0.27614,VFILMD)
*
**** TENSION ROLLER ASSEMBLY
**** AND LOOP TENSION CALCULATIONS
*
      TENST=LOOPST*KTAKSH
      TEN = KSUPSH*(LCOPSS-2*DISP)
      DISPAC = (2.*TEN - KD*DISPVE - KSPRIN*DISTEN)/MDAN
      DISPVE = INTGRL(-0.89569,DISPAC)
      DISP = INTGRL(0.13847,DISPVE)
      DISTEN =OFFSET + DISP
NOSORT
      IF (DISTEN.GE.00.0.AND.DISTEN.LE.2.0) GO TO 30
         DISPAC = 0.0
         DISPVE = 0.0
         DISP = - OFFSET
         IF (DISTEN.LT.1.0) GO TO 30
            DISP = 2.0 - OFFSET
            TEN = KSUPSH*(LOOPSS-2*DISP)
   30 CONTINUE
      IF (TEN.LT.0.0) TEN = 0.0
      IF (TENST.LT.0.0) TENST = 0.0
SORT
*
*
FINISH  RS = 1.0625,RT=3.25,LENGT=5400.
METHOD RECT
CONTRL FINTIM = 0.501001, DELT = 0.0000001
```

APPENDIX D

PROGRAM LISTING FOR THE PHASE LOCKED LOOP CONTROLLED CAMERA
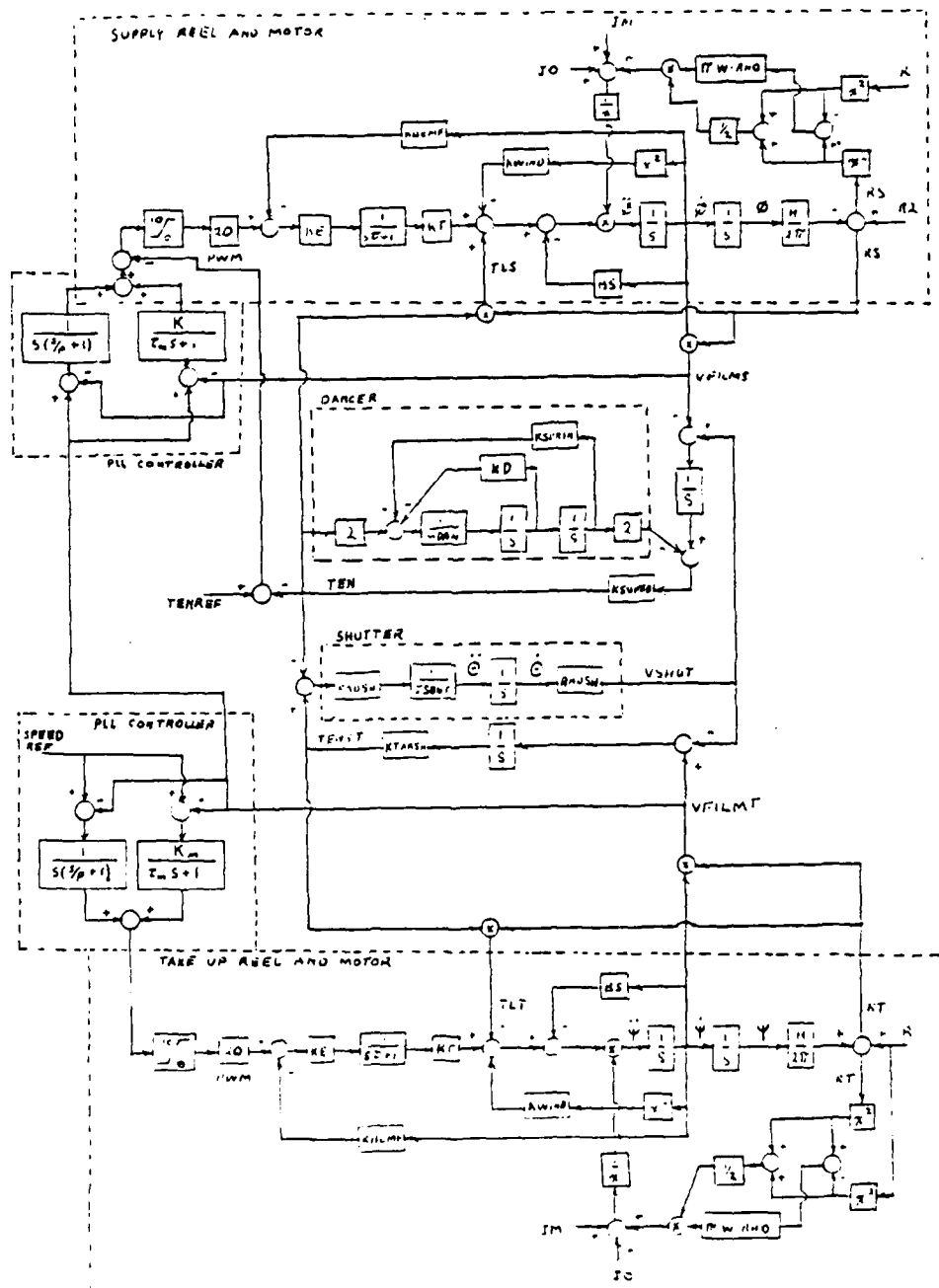
Figure D.1   System Block Diagram: Phase Locked Loop
Control of Both Reels

```
CONST  JO = .090984,KTS=3.6800,TAU=.000250,R2=3.25,R=1.0625
CONST  W=0.620,H=.0055,KBEMF=0.0334230,KE=2.500,JM=0.0060
CONST  BS=0.000143,KD=10.,KSPRIN=320,MDAN=.0074,RHO=0.00331
PARAM  VS=200.0,TENREF=160.,KTEN=.5,KTAKSH=3609,KSUPSH=5507
PARAM  JSHUT=.001344,RADSH=0.63,VFILMR=94247.78,DUR=.000055
INTGER N,A,NPLOT,FLAG
PARAM  A=0,N=1,NPLOT=1,OFFSET=1.016,POLE1=2000.0,FLAG=0
****
****  THE FOLLOWING IS A LIST OF THE
****  CONSTANTS AND THEIR DIMENSIONS
****
****  JM -MOTOR MOMENT OF INERTIA (IN-OZ-SEC**2)
****  JO- EMPTY REEL MOMENT OF INERTIA (IN-OZ-SEC**2)
****  KIS - SUPPLY MOTOR TORQUE CONSTANT (IN-OZ/AMP**2)
****  KBEMF - BACK EMF CONSTANT (VOLTS/RAD/SEC)
****  W - FILM WIDTH (IN)
****  H - FILM THICKNESS (IN)
****  RHO - FILM DENSITY (OZ/IN**3)
****  R2 - OUTSIDE RADIUS OF REEL (IN)
****  R - INSIDE RADIUS OF REEL (IN)
****  TAU -MOTOR TIME CONSTANT = LM/RM - DIMENSIONLESS
****  KE - MOTOR GAIN CONSTANT =1/RM (MHO)
****  BS - MOTOR DAMPING CONSTANT (IN-OZ/RAD/SEC)
****  KD - DANCER PULLEY DAMPING CONSTANT (OZ/IN/SEC)
****  KSPRIN - DANCER PULLEY SPRING CONSTANT (OZ/IN)
****  MDAN - DANCER PULLEY MASS (SLUGS)
****  KTAKSH - FILM SPRING CONSTANT
*                   (TAKE UP REEL TO SHUTTER) (OZ/IN)
****  KSUPSH - FILM SPRING CONSTANT
*                   (SUPPLY REEL TO SHUTTER) (OZ/IN)
****  JSHUT - SHUTTER MOMENT OF INERTIA (IN-OZ-SEC**2)
****  RADSH - SHUTTER SPROCKET RADIUS (IN)
****
INITIAL
        POLE = 1./POLE1
        OMEGAR = 0.0
        PASOME = 0.0
        FLAG = 0
        OMEGAD = VFILMR
DYNAMIC
*
*   This section checks to see if the system is accelerating
* or declerating and sets the flag accordingly
*
        OMEGAR = VFILMR*(STEP(0.1))
        IF(LENG.GT.4700.) OMEGAR = 0.0
        IF(LENGT.GT.4700.) OMEGAR = 0.0
        IF (OMEGAR.GT.PASOME) FLAG =1
        IF (OMEGAR.LT.PASOME) FLAG = 0
        PASOME = OMEGAR
        SET = 0.0
        IF (Y1.GE.0.0) SET = 1.0
*
* These two lines set the tension for pretensioning or run
*
        TENREF = 160.0
        IF (FLAG.EQ.0) TENREF = 16.0
```

```
*
**  FILM SPEED ERROR GENERATION: TAKE UP REEL ****
*
        TENERR = TENREF - TEN
        TRGTAK = AMOD(LENGT,0.3)
        TRGTK1= 0.0
        IF (TRGTAK.GE.0.15) TRGTK1 = 1.0
        TRGTK2= 0.0
        IF (TRGTK1.GT.PASTK1) TRGTK2 = 1.
        TAKPLS = PULSE(TRGTK2,DUR)
        SIGTAK = INTGRL(0.0,TAKPLS)
        REF = 0.0
        REF1= 0.0
        IF (Y.GE. 0.00) REF = 1.0
        IF (REF.GT.PASREF) REF1=1.0
        REF2 = PULSE(REF1,DUR)
        OPT = INTGRL(0.0,REF2)
*
* THIS IS THE TWO STATE COUNTER FOR THE TAKE UP REEL
* THE FILM SIGNAL COUNTS UP AND THE REFERENCE DOWN
*
        IF (TRGTK1.GT.PASTK1) STATE = STATE + 1
        IF (REF.GT.PASREF) STATE = STATE - 1
        IF (STATE.GT.1) STATE = 1
        IF (STATE.LT.0) STATE = 0
        INTTAK = REALPL(4.7820,POLE,10.0*STATE)
        IF (SET.LE.PASSET) GO TO 40
          VOPT = OPT
          VSGTAK = SIGTAK
          OPT = 0.0
          SIGTAK = 0.0
          TAKDIF = 0.0
  40    CONTINUE
        VETAK = VOPT - VSGTAK
        VFMTAK = 50000000.*VETAK
        FINTAK =10.00*(5.0 - INTTAK)
*
**** FILM SPEED ERROR GENERATION: SUPPLY REEL ****
*
        TRGSUP = AMOD(LENG ,0.3)
        TRGSP1= 0.0
        IF (TRGSUP.GE.0.15) TRGSP1 = 1.0
        TRGSP2= 0.0
        IF (TRGSP1.GT.PASSP1) TRGSP2 = 1.
        SUPPLS = PULSE(TRGSP2,DUR)
        SIGSUP = INTGRL(0.0000191,SUPPLS)
        SIGREF = INTGRL(0.0000307,TAKPLS)
*
* THIS IS THE TWO STATE COUNTER FOR THE SUPPLY REEL
* FILM SIGNAL SUPPLY COUNTS UP AND TAKE UP COUNTS DOWN
*
        IF (TRGTK1.GT.PASTK1) STATE1 = STATE1 - 1
        IF (TRGSP1.GT.PASSP1) STATE1 = STATE1 + 1
        IF (STATE1.GT.1) STATE1 = 1
        IF (STATE1.LT.0) STATE1 = 0
        INTSUP = REALPL(8.0979,POLE,10.0*STATE1)
        IF (TRGTK1.LE.PASTK1) GO TO 50
          VSGREF = SIGREF
          SIGREF = 0.0
          VSGSUP = SIGSUP
          SIGSUP = 0.0
  50    CONTINUE
        VESUP = VSGREF - VSGSUP
        VFMSUP = 50000000.*VESUP
        FINSUP = 10.00*(5.0 - INTSUP)
        VCOMS= LIMIT(0.0,10.0,VFMSUP + FINSUP - TENERR)
        VCOMT= LIMIT(0.0,10.0,VFMTAK+ FINTAK)
        IF(FLAG.EQ.0) VCOMT= LIMIT(0.0,10.0,-(VFMTAK+FINTAK))
        IF(FLAG.EQ.0)VCOMS=LIMIT (0,10,-(VFMSUP+FINSUP-TENERR))
```

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```
*
* THESE LINES SAVE THE PAST VALUES FOR FUTURE REFERENCE
*
      PASTK1 = TRGTK1
      PASREF = REF
      PASSP1 = TRGSP1
      PASSET = SET
*
*
*************************************************************
*     THIS BLOCK USES THE INPUT FROM THE ERROR BLCCK Above
*  IT TC THE REFERENCE SIGNAL TO CREATE THE INPUT PULSE
*  TRAIN FOR THE MOTOR
*************************************************************
      IF (N.EQ.1)  VREF =200000.*(TIMES- A*.00005)+.00000001
      IF (N.EQ.2)  VREF = 10.-200000.*(TIMES-A*.00005)
      IF (VREF.GT.0.0.AND.VREF.LT.10.0) GO TO 10
      IF (VREF.LE.0.0) N = 1
      IF (VREF.GE.10.0)  N=2
      A = A + 1
 10   CONTINUE
      EAS = 0.0
      IF (VREF.LT.VCOMS) EAS = VS
      IF (IAS.GT.300.0) EAS = 0.0
      EAT = 0.0
      IF (VREF.LE.VCOMT) EAT = VS
      IF (IAT.GT.300.0) EAT = 0.0
      IF (FLAG.EQ.1) GO TO 100
        EAS = 0.0
        IF (VREF.LT.VCOMS) EAS =-VS
        IF (IAS.LT.-300.0) EAS = 0.0
        EAT = 0.0
        IF (VREF.LE.VCOMT) EAT =-VS
        IF (IAT.LT.-300.0) EAT = 0.0
 100  CONTINUE
      IF (OMEGAR.NE.0.0.OR.VFILMT.GE.0.25) GO TO 110
        PSI = 0.0
        PSIDOT = 0.0
        PSIDDT = 0.0
        EAT = 0.0
 110      CONTINUE
*
** ELECTICAL EQUATIONS FOR THE SUPPLY REEL ****
*
DERIVATIVE
      Y = SINE(0.0,OMEGAR,0.000196153)
      Y1= SINE(0.0,OMEGAD,0.000196153)
      BEMFS = KBEMF*PHIDOT
      IASE = (EAS-BEMFS)*KE
      IAS = REALPL(-125.33,TAU,IASE)
      TMS = KTS*IAS
*
** SUPPLY REEL MOMENT OF INERTIA **
*
      RS = R2-(PHI*H/(2.*PI))
      MS = PI*(RS**2-R**2)*W*RHO
      JSFILM = 0.5*MS*(RS**2+R**2)
      JS = JM + JO + JSFILM
*
** CALCULATION OF THE TORQUE
** DUE TO FILM TENSION AND WINDAGE
*
      TLS = TEN * RS
      TWSUP = 0.000016*(PHIDOT**2)
```

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```
*
** CALCULATION OF THE MOTOR
** ACCELERATION,VELOCITY,AND DISPLACEMENT
*
      PHIDDT = (TMS + TLS - TWSUP)/JS -BS*PHIDOT/JS
      PHIDOT = INTGRL(1504.9,PHIDDT)
      PHI = INTGRL(293.69,PHIDOT)
*
** CAICULATION OF THE ACTUAL FILM SPEED **
*
      VFILMS = RS * PHIDOT
      LENG = INTGRL(916.73,VFIIMS)
      FRAMES= VFILMS/0.3
****
*
**** TAKE UP REEL EQUATIONS ****
*
** ELECTICAL EQUATIONS FOR THE TAKE UP REEL ****
*
      BEMFT = KBEMF*PSIDOT
      IATE = (EAT-BEMFT)*KE
      IAT = REALPL(-40.031,TAU,IATE)
      TMT = KTS*IAT
*
** TAKE UP REEL MOMENT OF INERTIA **
*
      RT = R +(PSI*H/(2.*PI))
      MT = PI*(RT**2-R**2)*W*RHO
      JTFILM = 0.5*MT*(RT**2+R**2)
      JT = JM + JO + JTFILM
*
** CALCULATION OF THE TORQUE
** DUE TO FILM TENSION AND WINDAGE
*
      TLT = TEN * RT
      TWTAK = .000016*(PSIDOT**2)
*
** CALCULATION OF THE MOTOR
** ACCELERATION,VELOCITY,AND DISPLACEMENT
*
      PSIDDT = (TMT - TLT -TWTAK)/JT -BS*PSIDOT/JT
      PSIDOT = INTGRL(2720.9,PSIDDT)
      PSI = INTGRL(675.29,PSIDCT)
*
** CAICULATION OF THE ACTUAL FILM SPEED **
*
      VFILMT = RT * PSIDOT
      LENGT= INTGRL(917.09,VFIIMT)
      FRAMET= VFILMT/0.3
*
**** CALCULATIONS CONCERNING THE SHUTTER ASSEMBLY ****
*
      THEDDT=RADSH*(TENST-TEN)/JSHUT
      THEDOT=INTGRL(7141.2,THEDDT)
      VSHUT=RADSH*THEDOT
*
***** AMOUNT OF FILM IN THE LOCP *****
*
      VDIFFT=VFILMT-VSHUT
      VDELT=VSHUT-VFILMS
      LCOPST=INTGRL(0.0478347,VDIFFT)
      LUOPSS=INTGRL(0.3058300,VDELT)
      VFILMD = VFILMT - VFILMS
      DELTL = INTGRL(0.35367000,VFILMD)
```

```
*
**** TENSICN ROLLER ASSEMBLY AND
**** LOOP TENSION CALCULATIONS
*
      TENST=LOOPST*KTAKSH
      TEN = KSUPSH*(LOOPSS-2*DISP)
      DISPAC = (2.*TEN - KD*DISPVE - KSPRIN*DISTEN)/MDAN
      DISPVE = INTGRL(-2.71870,DISPAC)
      DISP = INTGRL( 0.1371400,DISPVE)
      DISTEN =OFFSET + DISP
NOSORT
      IF (DISTEN.GE.00.0.AND.DISTEN.LE.2.0) GO TC 30
         DISPAC = 0.0
         DISPVE = 0.0
         DISP = - OFFSET
         IF (DISTEN.LT.2.0) GO TO 30
            DISP = 2.0 - OFFSET
            TEN = KSUPSH*(LOOPSS-2*DISP)
  30  CONTINUE
      IF (TEN.LT.0.0) TEN = 0.0
SORT
SAMPLE
NOSORT
      IF (TIME.GT.0.4.AND.TIME.LT.0.4010) CALL SAVE (H3)
SORT
*
*
FINISH  RS = 1.0625,RT=3.25,LENGT=5400.
METHOD RECT
CONTRL FINTIM = 0.505001, DELT = 0.0000001,DELS=.000001
```
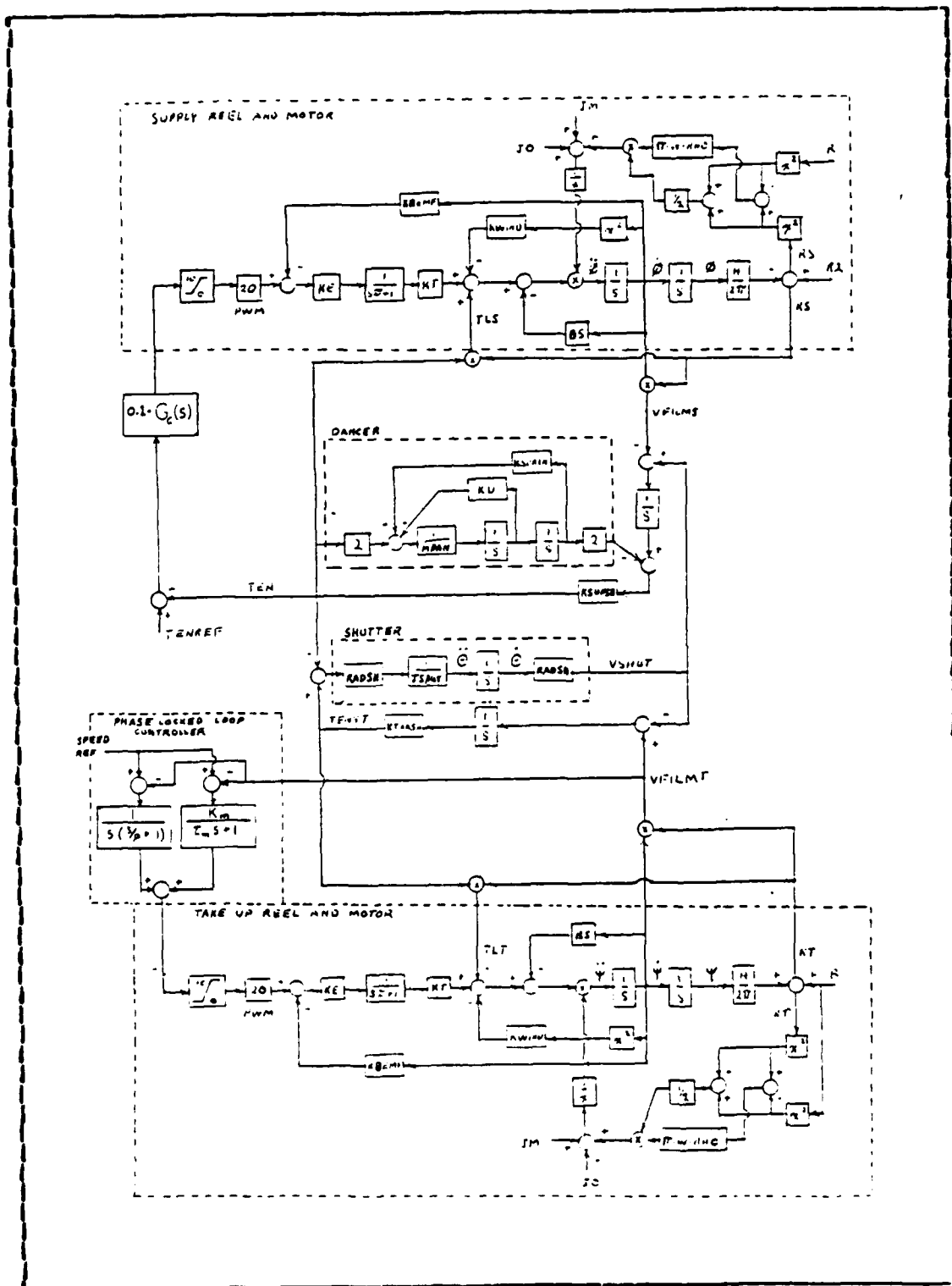
Figure D.2   System Block Diagram: Phase Locked Loop Control of Take Up Reel, Tension Loop Control of Supply Reel

```
CONST JO = .090984,KTS=3.6800,TAU=.000250,R2=3.25,B=1.0625
CONST W=0.620,H=.0055,KBEMF=0.0334230,KE=2.500,JM=0.0060
CONST BS=0.000143,KD=10.,KSPRIN=320.,MDAN=.0074,RHO=0.00331
PARAM VS=200.0,TENREF=160.,KTEN=.5,KTAKSH=3609.,KSUPSH=5507
PARAM JSHUT=.001344,RADSH=0.63,VFILMR=94247.78,DUR=.000055
INTGER N,A,NPLOT
PARAM A=0,N=1,NPLOT=1,OFFSET=1.016,POLE1=2000.0
PARAM POLE1C=200000,ZERO1C=20,POLE2C=100000,ZERO2C=1000
****
**** THE FOLLOWING IS A LIST OF THE
**** CONSTANTS AND THEIR DIMENSIONS
****
**** JM -MOTOR MOMENT OF INERTIA (IN-OZ-SEC**2)
**** JO- EMPTY REEL MOMENT OF INERTIA (IN-OZ-SEC**2)
**** KIS - SUPPLY MOTOR TORQUE CONSTANT (IN-OZ/AMP**2)
**** KBEMF - BACK EMF COMSTANT (VOLTS/RAD/SEC)
**** W - FILM WIDTH (IN)
**** H - FILM THICKNESS (IN)
**** RHO - FILM DENSITY (OZ/IN**3)
**** R2 - OUTSIDE RADIUS OF REEL (IN)
**** B - INSIDE RADIUS OF REEL (IN)
**** TAU -MOTOR TIME CONSTANT = LM/RM - DIMENSIONLESS
**** KE - MOTOR GAIN CONSTANT =1/RM (MHO)
****
INITIAL
        OMEGAR = VFILMR
        POLE = 1./POLE1
        MULT1 = POLE1C/ZERO1C
        MULT2 = POLE2C/ZERO2C
DYNAMIC
*
** FILM SPEED ERROR GENERATION: TAKE UP REEL ****
*
        TRGTAK = AMOD(LENGT,0.3)
        TRGTK1= 0.0
        IF (TRGTAK.GE.0.15) TRGTK1 = 1.0
        TRGTK2= 0.0
        IF (TRGTK1.GT.PASTK1) TRGTK2 = 1.
        TAKPLS = PULSE(TRGTK2,DUR)
        SIGTAK = INTGRL(0.0,TAKPLS)
        REF = 0.0
        REF1= 0.0
        IF (Y.GE. 0.00) REF = 1.0
        IF (REF.GT.PASREF) REF1= 1.0
        REF2 = PULSE(REF1,DUR)
        OPT = INTGRL(0.0,REF2)
        IF (TRGTK1.GT.PASTK1) STATE = STATE + 1
        IF (REF.GT.PASREF) STATE = STATE - 1
        IF (STATE.GT.1) STATE = 1
        IF (STATE.LT.0) STATE = 0
        INTTAK = REALPL(0.0000,POLE,10.0*STATE)
        IF (REF.LE.PASREF) GO TO 40
            VOPT = OPT
            VSGTAK = SIGTAK
            OPT = 0.0
            SIGTAK = 0.0
            TAKDIF = 0.0
 40     CONTINUE
        VETAK = VOPT - VSGTAK
        VFMTAK = 50000000.*VETAK
        FINTAK =10.00*(5.0 - INTTAK)
*
**** FILM SPEED ERROR GENERATICN: SUPPLY REEL ****
*
        TENERR = TENREF - TEN
        TENSIA = ZEROPL(0.0,ZERO1C,POLE1C,TENERR*MULT1)
        TENSIG = ZEROPL(0.0,ZERO2C,POLE2C,TENSIA*MULT2)
        VCOMS= LIMIT(0.0,10.0,0.10*(- TENSIG))
        VCOMT= LIMIT(0.0,10.0,VFMTAK+ FINTAK)
```

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```
      PASTK1 = TRGTK1
      PASREF = REF
      PASSP1 = TRGSP1
*
*
************************************************************
*    THIS BLOCK USES THE INPUT FROM THE PLL ERROR BLOCK
*  ANC COMPARES IT TO THE REFERENCE SIGNAL TO CREATE THE
*  INPUT POWER PULSE TRAIN FOR THE MOTOR
************************************************************
      IF (N.EQ.1) VREF =200000.*(TIMES- A*.00005)+.0000001
      IF (N.EQ.2) VREF = 10.-200000.*(TIMES-A*.00005)
      IF (VREF.GT.0.0.AND.VREF.LT.10.0) GO TO 10
      IF (VREF.LE.0.0) N = 1
      IF (VREF.GE.10.0) N=2
      A = A + 1
  10  CONTINUE
      EAS = 0.0
      IF (VREF.LT.VCOMS) EAS = VS
      IF (IAS.GT.300.0) EAS = 0.0
      EAT = 0.0
      IF (VREF.LE.VCOMT) EAT = VS
      IF (TEN.GT.320.0) EAT = 0.0
      IF (IAT.GT.300.0) EAT = 0.0
*
** ELECTICAL EQUATIONS FOR THE SUPPLY REEL ****
*
DERIVATIVE
      Y = SINE(0.0,OMEGAR,0.0)
      BEMFS = KBEMF*PHIDOT
      IASE = (EAS-BEMFS)*KE
      IAS = REALPL(-66.651,TAU,IASE)
      TMS = KTS*IAS
*
** SUPPLY REEL MOMENT OF INERTIA **
*
      RS = R2-(PHI*H/(2.*PI))
      MS = PI*(RS**2-R**2)*W*RHO
      JSFILM = 0.5*MS*(RS**2+R**2)
      JS = JM + JO + JSFILM
*
** CALCULATION OF THE TORQUE DUE TO
** FILM TENSION AND WINDAGE
*
      TLS = TEN * RS
      TWSUP = 0.000016*(PHIDOT**2)
*
** CALCULATION OF THE MOTOR ACCELERATION,
** VELOCITY,AND DISPLACEMENT
*
      PHIDDT = (TMS + TLS - TWSUP)/JS -BS*PHIDOT/JS
      PHIDOT = INTGRL(1649.1,PHIDDT)
      PHI = INTGRL(597.20,PHIDOT)
*
** CALCUIATION OF THE ACTUAL FILM SPEED **
*
      VFILMS = RS * PHIDOT
      LENG = INTGRL(1784.8,VFILMS)
      FRAMES= VFILMS/0.3
****
*
**** TAKE UP REEL EQUATIONS ****
*
** ELECTICAL EQUATIONS FOR THE TAKE UP REEL ****
*
      BEMFT = KBEMF*PSIDOT
      IATE = (EAT-BEMFT)*KE
      IAT = REALPL(12.961,TAU,IATE)
      TMT = KTS*IAT
```

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```
*
** TAKE UP REEL MOMENT OF INERTIA **
*
      RT = R +(PSI*H/(2.*PI))
      MT = PI*(RT**2-R**2)*W*RHO
      JTFILM = 0.5*MT*(RT**2+R**2)
      JT = JM + JO + JTFILM
*
** CALCULATION OF THE TORQUE DUE TO
** FILM TENSION AND WINDAGE
*
      TLT = TEN * RT
      TWTAK = .000016*(PSIDOT**2)
*
** CALCULATION OF THE MOTOR ACCELERATION,
** VELOCITY,AND DISPLACEMENT
*
      PSIDDT = (TMT - TLT -TWTAK)/JT -BS*PSIDOT/JT
      PSIDOT = INTGRL(2181.7,PSIDDT)
      PSI = INTGRL(1142.4,PSIDOT)
*
** CALCULATION OF THE ACTUAL FILM SPEED **
*
      VFILMT = RT * PSIDOT
      LENGT= INTGRL(1785.0,VFILMT)
      FRAMET= VFILMT/0.3
*
**** CALCULATIONS CONCERNING THE SHUTTER ASSEMBLY ****
*
      THEDDT=RADSH*(TENST-TEN)/JSHUT
      THEDOT=INTGRL(7142.2,THEDDT)
      VSHUT=RADSH*THEDOT
*
***** AMOUNT OF FILM IN THE LOOP *****
*
      VDIFFT=VFILMT-VSHUT
      VDELT=VSHUT-VFILMS
      LOOPST=INTGRL(0.0485203,VDIFFT)
      LOOPSS=INTGRL( 0.1447800,VDELT)
      VFILMD = VFILMT - VFILMS
      DELTL = INTGRL( 0.1933000,VFILMD)
*
**** TENSION ROLLER ASSEMBLY AND
**** LOOP TENSION CALCULATIONS
*
      TENST=LOOPST*KTAKSH
      TEN = KSUPSH*(LOOPSS-2*DISP)
      DISPAC = (2.*TEN - KD*DISPVE - KSPRIN*DISTEN)/MDAN
      DISPVE = INTGRL( 1.03040,DISPAC)
      DISP = INTGRL( 0.0563509,DISPVE)
      DISTEN =OFFSET + DISP
NOSORT
      IF (DISTEN.GE.00.0.AND.DISTEN.LE.2.0) GO TO 30
          DISPAC = 0.0
          DISPVE = 0.0
          DISP = - OFFSET
          IF (DISTEN.LT.2.0) GO TO 30
              DISP = 2.0 - OFFSET
              TEN = KSUPSH*(LOOPSS-2*DISP)
   30 CONTINUE
      IF (TEN.LT.0.0) TEN = 0.0
SORT
FINISH  RS = 1.0625,RT=3.25,LENGT=5400.
METHOD RECT
CONTRL FINTIM = 0.605001, DELT = 0.0000001,DELS=.000001
```

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